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February 8, 1999

In reply refer to: E-16-N42

Office of Naval Research
Program Officer, Judah M. Goldwasser
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Subject: **Final Technical Report W/ SF-298**
Project Director(s): Dr. Ben T. Zinn
Telephone No.: (404)894-3033
Contract No.: N00014-96-1-1196
Prime No.: N/A
"CONTROL OF SLUDGE DESTRUCTION IN SHIPBOARD INCINERATORS"
Period Covered: 960801 through 990131

The subject report is forwarded in conformance with the contract/grant specifications.

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
Jan. 31, 1999

3. REPORT TYPE AND DATES COVERED
08/01/96 - 01/31/99

4. TITLE AND SUBTITLE
Final Technical Report: Control of Sludge Destruction in Shipboard Incineration

5. FUNDING NUMBERS
G-N00014-96-1-1196

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Center Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19990211 001

11. SUPPLEMENTARY NOTES COR:

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Navy is interested in developing an actively controlled sludge incinerator using pulse combustion technology. This study is aimed at determining the feasibility, developing the technology to construct a suitable pulse combustor, and examining the benefits. Two approaches have been taken towards developing a suitable pulse combustor; the development of a tunable pulse combustor that can force resonant oscillations in the incinerator, and developing a high amplitude pulse combustor to generate non-resonant oscillations. While tunable combustors offer certain advantages, they currently have shortcomings, such as the inability to operate on liquid fuels. Therefore, a fixed-frequency combustor is currently a more practical approach. Tests showed that the pulse combustor exhaust can atomize a stream of liquid, which may allow replacing the currently used two-phase atomizer. Pulsed incineration tests were performed using a gas fired burner that operated at 80Hz, 240Hz, or in steady state mode, allowing comparisons to be drawn between different modes of excitation. Heat losses from the incinerator were greatly increased by pulsations, and the combustor emitted roughly 50% less nitrogen oxides when pulsating. Despite increased heat losses, the evaporative efficiency of the incinerator was typically 50% greater when pulsed. Methanol and sugar solutions were tested as waste surrogates, but low chamber temperatures resulted in unreliable results.

14. SUBJECT TERMS Incineration, pulse combustion, acoustic driving, spray drying, nitrogen oxides

15. NUMBER OF PAGES
72

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified			

Final Technical Report:

Control of Sludge Destruction in Shipboard Incinerators

ONR Grant No. N00014-96-1-1196

January 31, 1999

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Abstract

The Navy is interested in the development of a novel, actively controlled, shipboard sludge incinerator using state of the art pulsating combustion technology. This study is aimed at determining the feasibility of such an incinerator, developing the technology to construct a suitable pulse combustor for exciting high amplitude velocity oscillations in the incinerator, and examining the benefits obtained from this technology. Two approaches have been taken towards the development of a suitable pulse combustor. The first approach was the development of a tunable pulse combustor that can force resonant oscillations in the incinerator chamber. The second approach was to develop a high amplitude, low frequency pulse combustor that can generate non-resonant oscillations in the incinerator chamber. While tunable systems are more attractive for the generation of high amplitude oscillations in the incinerator, they currently have shortcomings, such as their inability to operate on liquid fuels. A single frequency, oil burning pulse combustor was demonstrated, and the use of this type of combustor appears to be the more practical approach at this time. Tests have been performed to show that the hot, oscillating exhaust of a pulse combustor can be used to atomize a stream of liquid, and that this may be useful for replacing the two-phase atomizer currently used to spray sludge into the incinerator. Pulsed incineration tests were performed using a gas fired burner that could be operated at 80Hz, 240Hz, and in steady state mode. Operation in the 80Hz mode modeled the oil burning pulse combustor. The use of this combustor allowed comparisons to be drawn between different modes of excitation, which could not be achieved using the oil burner. The heat losses from the incinerator chamber were greatly increased in the presence of pulsations, and the gas fired pulse combustor was shown to emit roughly 50% less nitrogen oxides when operated in a pulsating mode. Despite increased heat losses and the subsequent lower chamber temperatures, the evaporative efficiency of the incinerator was typically 50% greater when oscillations were excited in the chamber. Tests were also performed in which methanol and sugar solutions were used as liquid waste surrogates, but low chamber temperatures resulted in unreliable results.

Acknowledgements

The authors gratefully acknowledge the financial support of the Office of Naval Research. This program was sponsored under Grant No. N00014-96-1-1196.

Introduction

Increasingly strict national and international regulations governing environmental protection are forcing the military to become more responsible in the disposal of generated wastes. The Navy will no longer be able to dispose of paper, food scraps, and sewage by dumping these materials overboard. The main priority of Naval vessels, however, is to be combat ready. Therefore, any means to effectively handle these wastes must be both simple to operate, to minimize time investment of the crew, and small, so that the use of valuable cargo and crew space is minimized.

The objective of this program is to investigate the feasibility and benefits of a novel, compact, shipboard sludge incinerator using pulsating combustion technology. Shipboard sludge incinerators are currently being used by the Navy to incinerate black water consisting of 5% organic matter and 95% water. In the future, the percentage of water in the sludge will be reduced by use of membranes, and oils will be added to the remaining sludge prior to its incineration. The Navy would like to incinerate this sludge in a modified version of its current shipboard sludge incinerator, see Fig. 1, and is seeking technologies that will increase the throughput of its sludge incinerators while minimizing emissions of hazardous pollutants. Recent studies have indicated that this could be accomplished by actively controlling the incineration process with acoustic excitation[1,2]. Under this program, the feasibility and performance of an actively controlled, pulsating sludge incinerator that aims to simplify current shipboard incinerator design, increase its maximum sludge throughput, reduce emissions and lower fuel consumption are investigated.

It has been demonstrated that the presence of acoustic oscillations and flow pulsations can increase the rates of transport processes. Patera et. al.,[3,4] for example, have shown that mixing and heat transfer rates of laminar flow in a channel increased when the shear layer was destabilized using flow oscillations at properly chosen frequencies. A number of studies have provided evidence that mass[5] and heat[6,7,8] transfer rates are increased by acoustic oscillations. The physical mechanisms responsible for these increases are not entirely understood. Evidence[6,9] suggests that the increased transport rates are due to the excitation of turbulence and vortical structures by the acoustic oscillations. Vermeulen et al.[10] showed that flow oscillations reduce flow stratification and improve mixing, which can result in the elimination of localized pockets

of high temperature gas, or "hot spots", in a combustor. Rapid mixing is critical in liquid waste incinerators because evaporating droplets of waste generate fuel rich regions in the incinerator, which can result in the emission of soot, CO, and unburned hydrocarbons if proper mixing and combustion do not occur rapidly. Also, "hot spots" may be the cause of increased thermal nitrogen oxide production by the Zeldovich mechanism.

Several investigations of pulse combustors suggest that when combustion occurs in an oscillatory flow field, the combustion time is reduced and combustion efficiencies are increased with respect to combustion in a steady flow field. Lyman[11] for example, showed that pulsations increased the burning rates of individual coal particles, and Zinn et al.[12] found that unpulverized coal nuggets can be burned in a Rijke type pulse combustor with high combustion efficiency while utilizing little excess air. Bai [13] showed that heavy fuel oils, which are generally difficult to burn, can be burned with high combustion efficiencies in a pulse combustor specifically designed for this purpose.

The ability of a pulse combustor to act as a sludge atomizer was also investigated under this program. The interaction between a stream of sludge and the large amplitude velocity oscillations in the exhaust flow of a pulse combustor may be capable of atomizing the sludge into small droplets that will readily evaporate and burn. Since the pulsating stream of hot combustion products atomizes the sludge, evaporation of the generated droplets and combustion of their organic constituents will start simultaneously with their atomization. The exhaust flow of the pulse combustor will entrain the generated droplets and set them into a swirling motion within the incinerator volume, thus increasing their dispersion and residence time within the incinerator. The use of the pulse combustor to atomize the sludge will eliminate the need for a separate two-fluid atomizer that is currently used to atomize the sludge. A similar approach has been successfully used by Bepex[14] to spray dry various foods and pharmaceuticals. In the Bepex pulse dryer, slurry is injected directly into the exhaust flow of a pulse combustor where it is atomized, heated and partially vaporized. The resulting mixture of gases, droplets and partially dried particles is transported into a large dryer volume, where the drying process is completed in a pulsating environment. The dried material is separated from the flow and collected in the exhaust system. A sludge incinerator is similar to a spray dryer, except that enough energy must be added to the sludge not only to dry it, but also to ignite and burn its combustible content.

Research Accomplishments

Combustor Development:

A primary goal this project was the development a pulse combustor capable of exciting large amplitude velocity oscillations in the shipboard sludge incinerator under typical operating conditions. Since the largest amplitudes of oscillation for a fixed driving force are achieved by driving at a resonant frequency of the chamber, it was originally decided to design a combustor that can operate at one of these frequencies. In order to excite the first transverse resonant acoustic mode in the incinerator, calculations predict that the combustor must be able to pulse at approximately 650Hz. Higher frequencies are required to excite higher acoustic modes and combined longitudinal and transverse modes. Currently existing pulse combustors typically operate below 500Hz. One technique, then, for exciting high amplitude velocity oscillations in the incinerator is to develop a tunable pulse combustor that can be tuned to one of these high frequencies while providing the heating rates necessary for sludge incineration. Two operational approaches were considered in the development of the pulse combustor: mechanical tuning and electronically controlled fuel injection. Pulsations can be forced at off-resonant frequencies in the incinerator chamber, but more acoustic energy is required from the driver to achieve high amplitudes. Since pulse combustors that are more amenable to the combustion of fuel oil tend to operate at frequencies below the resonances of the incinerator chamber, the use of low frequency forcing was also tested. An oil burning pulse combustor, based on a design by Severyanin[15], was constructed and tested.

Mechanically tunable pulse combustor

Previous data from a mechanically tuned pulse combustor with a power rating of 0.6 MMBtu/hr indicated that the maximum pulsing frequency of this combustor was approximately 430Hz. Sivasigaram and Whitelaw[16] have suggested that the maximum pulsing frequency of a flame holder-type combustor is dependent on the diameter of the combustor. Using Sivasigaram and Whitelaw's empirical relations, a mechanically tunable pulse combustor was developed with a smaller diameter and a corresponding reduction in capacity. Schematics of the small,

mechanically tunable pulse combustor and the model incinerator with the combustor attached are presented in Fig. 2. The combustor is designed for gaseous fuels, and was operated on natural gas. This pulse combustor can operate at frequencies up to 1000Hz, which is well above the minimum frequency required to drive resonant acoustic oscillations in the chamber of the shipboard sludge incinerator. Unfortunately, the power capacity was reduced to 170 MBTU/hr, which is much lower than the 1MMBtu/hr power of the steady oil burner used with the current generation sludge incineration system. In order to make use of such a combustor, it would either have to be used in conjunction with a steady state burner that provided the balance of the necessary heat input to the incinerator, or multiple pulse combustors would need to be used.

A graph of the amplitude of the pressure oscillations excited in the incinerator chamber for various flame holder positions in the combustor is shown in Fig. 3. The figure shows that even operating at a low heat output, the burner can excite resonant oscillations on the order of 155dB in the chamber. Figure 4 shows how the pressure amplitude of the second longitudinal/first tangential combined resonant mode varies with the heat output of the combustor. As expected, the acoustic amplitude increases with combustor power, but the functional relationship is not currently understood.

Electronically controlled pulse combustor

A novel pulse combustor that can be used in conjunction with a previously developed, electronically controlled fuel actuator system was designed and constructed. This burner is referred to as the Pulsed Flame Tube Driver (PFTD). The concept of the PFTD is that a compact combustor mounted to the wall of the incinerator chamber would, in the absence of forced fuel modulation, couple acoustically to pressure oscillations in the chamber, and the resulting feedback loop would cause the system to resonate. A schematic of the PFTD configured without the actuator is shown in Fig. 5. The fuel injector actuator, together with appropriate control software, provides a secondary stream of modulated fuel to the combustor at frequencies and phases determined in real-time from sensor measurements so that the operator can select the mode and amplitude of the oscillations. The configuration of the PFTD with the secondary fuel injector and the actuator present is shown in Fig. 6.

The performance of the PFTD without secondary fuel modulation was tested in two configurations. In the first configuration, shown in Fig. 7A, the PTFD was mounted on the side of the incinerator chamber in a position similar to the mounting of the current steady burner used on the shipboard incinerator. It was expected that in this position, coupling would be achieved with either a transverse mode of the chamber or with a three-dimensional combination of a longitudinal mode with a transverse mode. The natural gas supply rate was varied from 50 to 350 MBtu/hr, the flame-holder location varied over its full range, and the equivalence ratio was varied from 1 to lean blow-off. Under no conditions was the burner spontaneously unstable, which means that the expected feedback loop did not occur.

In the second configuration tested, shown in Fig. 7B, the PFTD was mounted on the upstream end of the incinerator chamber, coaxially. In this configuration, if coupling were to occur, it was expected to be with a longitudinal mode of the chamber, since the frequencies of the radial modes are quite high, and the radially symmetric geometry does not favor the excitation of transverse modes. If the PFTD coupled with a longitudinal mode, it would be suspected that there was some geometrical difficulty coupling with the tangential modes. The same range of parameters from the previous configuration was tested. In this configuration, when the heat input was greater than 300 MBtu/hr, the equivalence ratio less than 0.8, and the flame-holder was pulled back to give very high velocities, the system pulsed at 1270Hz at low amplitude (135dB). This frequency corresponds to a quarter wave oscillation in the PFTD itself, and is approximately the same as the seventh longitudinal mode of the chamber. While this oscillation does show coupling in the system, it is behaving as not designed, but instead as a single frequency device. It is believed that the reason this mode was not seen in the previous configuration is that the frequency did not correspond to any mode that could be driven in the tank from where the burner was located.

The actuator was added to the PFTD to provide fuel modulation without the necessity of natural feedback. In order to separate the effects of the modulated fuel flow supplied by the actuator from the effects of pressure feedback on the air and primary fuel lines, the air and primary fuel inlets were choked for tests involving the actuated PFTD. When the actuated PFTD was mounted to the side of the incinerator chamber, configuration A, the fundamental

longitudinal mode could be excited at low amplitude. No higher frequencies or transverse modes could be excited.

Possible explanations for the inability of the PFTD to provide significant acoustic driving in the above-described test are:

1) the oscillatory flame does not couple with the pressure oscillations in the model incinerator
2) inability to produce an oscillating flame due to:
    a) the fuel injector actuator not providing an oscillatory fuel flow rate, or
    b) fuel flow rate oscillations are being fluid mechanically dissipated, or smeared out, before entering the combustion zone

In order to determine whether the PFTD is capable of coupling with a resonator more typical of common pulse combustors, the burner was mounted to several 4 in. IPS pipes, 65 in., 51 in., and 18 in. long. When attached to these pipe sections, oscillations occurred over a large range of fuel flow rates, equivalence ratios, and flame holder positions. These oscillations were at approximately 82Hz, 100Hz, and 250Hz, respectively, which corresponds to quarter wave, organ pipe oscillations in the PTFD/pipe combinations. In each case, the amplitude of oscillation was approximately 170dB in the PFTD. A graph showing the autospecta of the pressure measured inside the PFTD when it was attached to the 51-in. pipe for several tests is presented in Fig. 8. The PFTD concept has been proven by these tests to work in relatively small diameter pipes. It has been demonstrated that if the PFTD is located at the end of a resonating tube, it can drive high amplitude oscillations within the resonator. The driver and the resonating tube (the system is essentially a pulse combustor) can then be coupled to a larger chamber, and oscillations are driven in the chamber at a lower amplitude than that in the PFTD resonator. The intention of the PFTD was, however, to do away with the resonating pipe and use the chamber itself as the resonator. Tests using speakers mounted on resonating tubes and directly to the wall of the incinerator chamber have shown that using a resonator allows higher amplitudes to be driven using the same input power to the speaker.

To investigate the second item above, tests were performed with the actuated PFTD mounted on an 18 in. long, 4 in. IPS pipe section. The PFTD primary fuel and air inlets were choked to prevent a natural instability. In the original design configuration of the fuel injector, when 80% of the fuel was supplied through the primary fuel inlet and 20% of the fuel flow was modulated through the secondary fuel inlet, and the average equivalence ratio varied from 1 to lean blow-off, no significant oscillations were measured at any frequency. The conditions were then modified so that all the fuel was injected through the secondary injector, and the amplitude of modulation was 60% of the total fuel flow rate. The average equivalence ratio was set to 0.75, so that the instantaneous equivalence ratio varied from 0.3 to 1.2. With this extremely large fuel modulation, an oscillation could be driven a 250 Hz., the quarter wave mode, with a measured amplitude of 150 dB in the PFTD. This oscillation amplitude is an order of magnitude less than could be achieved without the actuator (by a spontaneous instability) when the air and primary fuel lines were not choked.

Because the unchoked PFTD can be spontaneously unstable when mounted to a 4" pipe section, the lack of pulsations using the fuel actuator and choked ports was apparently not due to an inability of the combustion process in the PFTD to drive pressure oscillations. The results of these tests did not show, however, whether the inability to drive oscillations was due to mixing of the secondary fuel oscillations before reacting or the inability of the actuator to provide a modulated fuel flow rate. To resolve this question, hot-wire anemometry was used to measure the flow rate of air modulated by the fuel injector actuator. This test showed that fuel injector actuator was performing as expected, and that the modulation amplitude was practically independent of frequency from 20 Hz. to over 1000 Hz. Therefore, the inability to drive oscillations in this configuration must be due to the smearing out of the secondary fuel oscillations before reaching the flame zone.

To test this conclusion, the secondary fuel injector was extended 1.5 in. downstream, so that the modulated fuel flow rate was injected closer to the flame zone. In addition, a detection system was added to measure the CH chemilumenescence of the flame, so that the reaction rate could be correlated with the displacement of the fuel actuator. The phase between the actuator displacement and the radiation gives an indication of the time delay between the fuel injection and the consumption of the injected fuel by the flame. Using the modified fuel injector and

closed-loop active control, an oscillation with an amplitude of 164dB at 265Hz. could be excited in the PFTD. The acoustic pressure spectrum measured using closed loop control is shown in Fig. 9. In this study, 25% of the fuel was introduced through the secondary fuel injector actuator, but only a 40% modulation amplitude was used (in other words, the modulation amplitude was approximately 10% of the total fuel flow rate). While this represents a factor of 5 increase over the pressure amplitude achieved with the previous fuel injector, it is still rather low. The flame would not stay ignited at higher modulation amplitudes.

It has been demonstrated that the use of secondary fuel injection at off-resonant frequencies can drive low amplitude oscillations at the injection frequency. Figure 10 shows the frequency spectrum of the acoustic pressure in the PFTD, attached to an 18" long pipe, with secondary fuel addition occurring at 220 Hz. The frequency corresponding to a quarter wave mode is approximately 300 Hz. in this case. The pressure amplitude excited by the fuel modulation in this example is 150dB. The radiation measurements show that oscillatory combustion is occurring at the fuel modulation frequency. This suggests that the sound is not simply being generated by the flow through the secondary fuel injector, as if it were a siren, but is actually being driven by the oscillatory combustion process. Phase measurements between the actuator displacement and the radiation show that, even with the increased injector length, the time delay between when the fuel is injected and when it is reacted is relatively large, indicating that mixing of the fuel pulses before combustion was at least partially to blame for the weak driving previously observed.

The relationship between the phase delay and the frequency is not linear. This means that the phase between the secondary fuel injection and the reaction of the secondary fuel is not purely based on a convection time delay. A further lengthening of the fuel injector by another 1.5" improved the performance in closed loop operation by 4 dB, to an amplitude of 168dB in the PFTD. This amplitude was nearly as loud as the natural instabilities that occur when the air and fuel inlets are not choked. When the PFTD was unchoked and the actuator was operated by the closed loop control system, the amplitude could be maximized at 173dB, a 3dB increase over the natural instability. This demonstrates that the actuated fuel system can be used to increase the amplitude of the combustor oscillations, and shows a 50% increase in the amplitude of the

oscillations. When the phase delay of the controller is changed to reduce the pulsation amplitude, the actuator provides a 75% reduction in the amplitude of the natural instability.

A liquid fuel actuator has been developed in conjunction with an AFOSR project. This liquid fuel actuator was used with the PFTD to determine whether a modulated spray of diesel oil could be used to control the pulsations in a naturally unstable gas burner. Modulation of the flow of fuel oil through the actuator has been confirmed using stroboscopic and high-speed photography. Testing, however, showed that there was little correlation between the modulations of the oil spray and the pressure in the combustor.

Oil Burning Low Frequency Pulse Combustor

The second approach taken to providing large amplitude velocity oscillations in the shipboard incinerator was the use of a low frequency pulse combustor to force bulk type pulsations in the chamber. To provide this driving, research was directed toward developing an oil burning pulse combustor suitable for application on a shipboard incinerator.

A single frequency, aerodynamically valved, oil burning pulse combustor was constructed. An illustration of the burner section is shown in Fig. 11. The combustor is self-aspirating after ignition. Like other combustor designs of this class, the burner consists of a combustion chamber, an aerodynamic valve, a fuel nozzle, an igniter, and a resonant tailpipe. The Severyanin design was chosen for this study because of its relatively simple design, the above average performance of the aerodynamic valve, and the fact that it performs well on No. 2 oil sprayed through a simple hollow cone nozzle without preheating. The burner constructed is capable of burning 850 MBtu/hr of kerosene type fuel oils, such as JP5. With minor design changes, a burner that can operate at over 1 MMBtu/hr can be readily constructed. As presently configured, the combustor operates at approximately 75 Hz, and when burning 700 MBtu/hr, has an acoustic pressure amplitude of 1.4 PSI RMS, or 174 dB.

A time trace of the dynamic pressure measured inside the combustion chamber of the oil burner is shown in Fig. 12. The combustor was operating at 700Mbtu/hr on diesel fuel. The peak pressure amplitude varies between 2 and 3PSIG, and the minimum pressure is somewhat more constant between cycles at about –1.6PSIG. The acoustic pressure autospectrum, Fig. 13, shows that the signal is dominated by a 75Hz oscillation, which represents the quarter wave mode of the

combustor tailpipe. Both even and odd harmonics are present, and their strength appears to drop off exponentially.

The effect of varying the fuel input to the burner is shown in Fig. 14. The lower limit of operation of the combustor is just over 400MBtu/hr. The maximum limit was chosen to be the point at which the flame extended back out through the air valve. This maximum limit of operation could be extended by forcing air into the air valve, but no data was collected under these conditions. The amplitude of the oscillations is shown to reach a minimum near 550MBtu/hr. The amplitude was also shown to be a function of the tailpipe length. Figure 15 shows the variations in the combustion chamber pressure amplitude when the length of the tailpipe was changed. The combustor failed to self-aspirate when the tailpipe length was shorter than 102in. or longer than 118in.

The frequency measured in the combustion chamber suggested that the tailpipe was resonating in a quarter wave mode, and this was confirmed by pressure measurements along the length of the tailpipe, shown in Fig. 16. The temperature distribution along the length of the tailpipe is shown in Fig. 17. The combustor was run with a fan cooling the outside of the tailpipe to prevent overheating of the metal. It is clear from the temperature measurements that the burning extends beyond the combustion chamber and partway down the tailpipe. No access was available to determine the maximum temperature, however.

Because this combustor is not tunable and the fundamental operating frequency is lower than any of the resonant frequencies of the incinerator chamber, tests were performed to determine whether the combustor could drive pulsations of significant amplitude in the chamber. The combustor was operated on natural gas for these tests. These tests were also intended to determine the effect of the incinerator chamber on combustor operating characteristics. The acoustic forcing from the pulse combustor was shown to excite the incinerator chamber to an acoustic pressure amplitude between 145 and 150dB. Figure 18 shows a typical autospectrum of the pressure measured at the head end of the incinerator chamber. The combustor was operating at 700MBtu/hr, with a combustion chamber SPL of 173dB. The autospectrum shows that, unlike the pressure in the combustion chamber, the harmonic content of the sound is quite high, even in the fourth harmonic. Often the second harmonic is observed to be the dominant frequency in the

incinerator. The phases between the acoustic pressure measured in the combustion chamber and the pressure signal measured at various locations in the incinerator chamber was measured for the first two harmonics and are plotted in Fig. 19. These plots show a roughly linear distribution, which indicates that the losses associated with waves of these frequencies are high, and that the oscillations are not resonant in the chamber. A comparison of the predicted resonances of the incinerator chamber and the frequencies of the first four harmonics in the incinerator chamber are shown in Fig. 20 as a function of the incinerator chamber temperature. The fundamental frequency of the pulse combustor is shown to be always below the resonant modes of the chamber. When the chamber temperature is approximately 550deg. f, however, the second and fourth harmonics of the combustor frequency match the frequencies of a longitudinal half wave and a full wave, respectively, in the incinerator chamber. When this condition is met, it becomes very easy for these frequencies to be driven to large amplitudes in the incinerator. This "temperature tuning" effect explains not only why the second harmonic of the combustor frequency is sometimes the dominant frequency inside the incinerator, but also why the overall sound pressure level varies strongly with time when the system is heating up. Figure 21 shows two time traces of the acoustic pressure measured at the head end of the incinerator chamber measured with different mean chamber temperatures. The difference in the harmonic content is evident. The operating characteristics of the pulse combustor itself were not noticeably altered by the attachment to the incinerator.

The incinerator model used in this study is a greatly simplified version of the Navy's current sludge incinerator. Therefore, no typical steady date performance data was available, and the ability to run non-pulsed tests was necessary for comparisons to be made between steady and pulsed incineration. A gas fired burner was developed, based on the mechanically tunable pulse combustor design, that allowed tests to be performed at two frequencies of driving as well as steady state without changing the fuel input or the equivalence ratio. The burner, shown schematically in Fig. 22, consisted of a small combustion chamber with a moveable flame holder that was mounted to the tailpipe of the oil burner. The low frequency of this burner approximately matches the operating frequency of the oil-fired burner, but the amplitude of operation is about 5dB lower in the gas burner.

Atomization Using A Pulse Combustor:

Tests were performed to determine if the exhaust from the pulse combustor could be utilized to atomize the sludge flow into the incinerator chamber. If injection of the sludge into the hot, oscillating flow of the pulse combustor exhaust can provide high quality atomization of the sludge, then the currently used, two-fluid atomizer will no longer be necessary. The main advantage of using the pulse combustor to atomize the sludge is that, since the sludge is delivered directly into the hot, oscillating exhaust gas, extremely rapid heat transfer will take place between the gas and liquid phase.

To test the ability of pulse combustor exhaust to atomize a stream of liquid, the small mechanically tunable pulse combustor developed earlier in this program was fitted with two removable liquid injectors near the end of the tailpipe; one radial and one coaxial with the exhaust gas flow. This combustor was chosen for these tests because it can easily be operated at the same fuel and air input rates with and without pulsations, simply by varying the flame holder and nozzle locations. A schematic of the atomization setup is shown in Fig. 23. In order to determine the effect of the pulsations on atomization, tests were performed with the combustor operating at 150 MBtu/hr with and without pulsations for various flow rates of water through the injectors. When pulsations were present, the pulse combustor was operated at about 600Hz and at an acoustic amplitude of 170dB at the flame holder. The tests were photographed digitally, and downloaded to a computer for processing. An average image was generated from 8 instantaneous images for each flow condition, and then the spreading angles of the generated sprays were measured from the images to give an indication of atomization efficiency. Figure 24 shows example images of the radially directed injection with and without pulsations, and Fig. 25 shows examples of the coaxially injected spray, with measurements used in the spreading angle calculations shown. It is clear from these pictures that the spreading rate of the spray is greatly increased by the presence of pulsations in the exhaust flow. The measured spreading angles for different water injection rates with and without pulsations present are shown in Fig. 26. The percentage change in spreading angle is also shown. While an increase in spreading angle does not directly correlate to faster heat exchange between the spray and the hot exhaust gas, it is logical that in order to disperse in a shorter distance the spray must be entraining more of the hot gases.

Tests were then performed using the fixed frequency, oil burning pulse combustor to determine the optimal location and orientation of liquid injection. The combustor was not attached to the incinerator chamber for these tests, so that the spray could be easily observed. Water was injected into the pulse combustor tailpipe both radially and axially at various positions along the length of the tailpipe, as shown schematically in Fig. 27. The residence time of the liquid spray in the hot, pulsating exhaust stream is maximized by injecting the liquid upstream in the tailpipe as close to the combustion chamber as possible. Three problems were observed in association with this technique, however. First, the graph in Fig. 27 shows that the farther upstream the liquid injection occurs, the lower the acoustic velocity amplitude it encounters at the exit of the inlet tube. A large acoustic velocity amplitude is necessary to provide the shear stress to atomize the liquid stream. Second, as the injection location was moved upstream in the tailpipe, a noticeable increase in the amount of soot emitted from the pulse combustor was observed. It appears that the combustion process extends some distance beyond the combustion chamber and into the tailpipe. When water is injected into the tailpipe upstream of the point at which the combustion process is completed, the water quenches the reaction and soot is emitted rather than burned. The third problem is that when the spray is generated upstream in the tailpipe, it tends to impinge upon the tailpipe walls, which can result in pooling of liquid, a buildup of solids, and poor quality secondary spraying from the end of the tailpipe. It was therefore decided that the intended benefit of upstream injection cannot be achieved, and that the best place to inject the liquid is just upstream of the tailpipe exit, so that no impingement of the spray on the walls occurs.

It was also observed that the spray produced using a radial injection scheme was very poorly distributed. The water tended to be sprayed in a sheet oriented in the plane of the injector, and small drops tended to one side of the sheet and large drops to the other. Coaxial injection, on the other hand, produced a axially symmetric spray with the larger drops concentrated toward the center. This latter distribution is preferred for use in the sludge incinerator.

Effects of Pulsations on Incineration Processes:

Tests were performed to determine whether acoustic forcing affects the sludge incineration process. In a related study also funded by ONR, Widmer et. al.[17] reported that no

measurable differences were observed between acoustic and steady tests in their incinerator. Our testing was directed towards validating this finding.

The pulsed incineration tests were performed using the gas fired burner, described above, that could be operated at 80Hz, 240Hz, and in steady state mode. The use of this combustor allowed comparisons to be drawn between different modes of excitation, which could not be achieved using the oil burner. Although previous results show that the highly oscillatory exhaust flow from the pulse combustor tailpipe can be used to effectively atomize a stream of liquid, a spray nozzle was used in these tests to provide the best possible uniformity of the spray between pulsing and steady burning tests. The spray nozzle was placed at the exit of the tailpipe and was oriented in the direction of the combustion gas flow. A schematic of the experimental setup used in the pulsed incineration studies is shown in Fig. 28.

Effect of pulsations on the incinerator characteristics

The autospectra of the acoustic pressure measured inside the combustion chamber in low and high frequency modes of operation are shown in Fig. 29. While a number of harmonics are present, the 80Hz signal is clearly dominant during low frequency operation, and 240Hz is the dominant frequency in high frequency operation. These represent quarter wave and three-quarter wave resonances of the tailpipe, respectively. Figure 30 shows the autospectra of the acoustic pressure measured in the incinerator chamber with low and high frequency driving present. In the low frequency driving case, the harmonics present in the incinerator chamber are as important as the driving frequency. In particular, the third and fourth harmonics are observed to be the same amplitude as the fundamental frequency. When the high frequency mode is used, however, the 240Hz driving signal clearly dominates other frequencies in the incinerator chamber.

Initial testing was performed to determine the effect of the acoustic driving on the temperature distribution inside of the incinerator chamber and the exhaust emissions. No liquid was injected during these tests. A time trace of the measured pressures and temperatures (see Fig. 28 for measurement locations) for a run in which the incinerator was heated up in steady burning mode and then switched after 10min. to low frequency mode is shown in Fig. 31. The fuel input was 268 MBtu/hr. Although the temperature of the combustion products leaving the tailpipe (T1) did not change significantly when the acoustic was initiated, the chamber and exhaust

temperatures dropped in the presence of acoustics, showing that the heat transfer to the outside walls of the incinerator was increased by the presence of pulsations. Figure 32 shows the effect of both low and high frequency acoustic forcing on the emissions form the incinerator. The exhaust concentrations of O_2 and CO_2 were unaffected by the presence of acoustic forcing. The NOx concentration, however, was reduced to approximately 50% of its steady burning value by both low and high frequency driving. The NOx emissions for a 270MBtu/hr burning rate were typically 50PPM (referenced to 3% O_2) without pulsations, 24PPM with low frequency driving, and 22PPM with high frequency driving. The lower NOx measurements shown in the graph are actual PPM, not referenced values. Because the oil burner cannot be run in a steady mode, it is not known whether or not oil combustion is similarly affected. The CO emissions from the natural gas burner were below the accuracy of the detector, due to the lean combustion mixtures used.

Pulsed water evaporation

Testing was carried out using a spray of water to determine whether or not the presence of pulsations affected the evaporation rate of the droplets. Tests were performed to determine the maximum water flow rate that could be evaporated in the incinerator chamber with a preset burning rate. In order to determine if the water spraying into the chamber was evaporating or collecting on the bottom of the incinerator, the temperature from thermocouple T3 (see Fig. 28), which was located on the bottom of the incinerator chamber, was monitored. When all the water was being evaporated, thermocouple T3 indicated the local gas temperature, which was normally above 212°f. If water began to pool on the bottom of the incinerator, however, the temperature measured at T3 would drop sharply to below boiling. Figure 33 shows the results of a test in which water was sprayed into the incinerator at 7.5GPH and the fuel input was 268 MBtu/hr. When the burner was operated in low frequency mode, all of the water was evaporated. When the burner was operated in steady mode, however, water would begin to pool on the bottom of the chamber, indicating that the water spray could not be entirely evaporated. Because of the measurement technique, there is a time delay between the change in acoustic amplitude and the response of the bottom surface temperature. Figure 34 shows that the emissions are not affected by the presence of the spray of water.

A search procedure was then implemented to quantify the maximum evaporation rate for a given fuel input and acoustic forcing mode. An example of this procedure is shown in Fig. 35. In this example, the fuel input rate was 268MBtu/hr and the burner was operated in low frequency mode. The water flow rate was initially set to a flow rate that was believed could be entirely evaporated under the current conditions, in this case 8.0GPH, and the incinerator was fired. When the incinerator had heated up enough to evaporate all the water at the initial flow rate, the rate was increased. If the water began to pool in the incinerator, the flow rate was reduced to an intermediate value. If, instead, after 20min. no liquid water had begun to collect in the incinerator, the flow rate would again be increased. The result of this example test was that the maximum flow rate that could be evaporated under these conditions was 8.4GPH. These tests were then repeated several times for each set of conditions, and the results were averaged. The run to run variation was typically within 5% of the mean value.

The results obtained from these tests are plotted in Fig. 36-38. From these figures it is clear that despite the increased heat losses from the incinerator chamber in the presence of acoustic forcing, the evaporation rate of water droplets is significantly greater. The amount of improvement that acoustic forcing provides varies with the operating conditions in a way that is not understood. Because of the inability to set the acoustic amplitude of the oscillations during testing and the competing effect of the wall heat losses, it may be difficult to determine that relationship in this experimental setup. It is interesting that the low frequency forcing consistently provides a slightly greater evaporation rate than low frequency forcing in these tests.

Pulsed liquid waste incineration

In order to determine the effect of pulsations on waste incineration, it was necessary to add fuel to the water being sprayed into the incinerator chamber. Because a spray nozzle was used to introduce the liquid to the incinerator, rather than the two-phase atomizer used in the Navy's current sludge incinerator, it was necessary to use fuels that were soluble in water to prevent clogging of the nozzle orifice. It should be noted that while one objective of the program was to utilize the atomizing capabilities of the pulse combustor exhaust, a spray nozzle was used to provide similar atomization characteristics during pulsing and steady burning tests. The two fuels tested under this program were methyl alcohol (methanol) and sucrose (refined cane sugar).

Tests were first performed with a solution of 8% methanol by weight in a balance of water, with a net heating capacity of approximately 6600BTU/gal., and 6.93 gal./hr. of the mixture were injected. The burner was operated at 270MBTU/hr, with equivalence ratio $\phi = 0.56$. Observation of the incinerator chamber showed that when no pulsations were present, a pale blue flame was visible just downstream of the nozzle. No flame was visible when pulsations were present. The exhaust gas concentrations of O_2, CO_2, and CO for a test in which no acoustic excitation was present are shown in Fig. 39. The burner was first operated with water spraying into the incinerator, then switched at 90sec. to the methanol mixture, and then switched back to water at 180sec. The observed reduction in the amount of exhaust O_2 and the associated increase in the CO_2 concentration when the methanol was sprayed indicates that at least some of the methanol is being burned. Based on the utilization of the available oxygen, it was calculated that under steady flow conditions, 39% of the injected methanol was burned. This efficiency is low due to the relatively cool temperatures associated with the uninsulated carbon steel incinerator model used for these tests. The chamber temperature just downstream of the combustor tailpipe was approximately 700°f in steady tests, and dropped to about 450°f at the exhaust entrance. When pulsations were present, the combustion efficiency was greatly reduced. Figures 40 and 41 show the exhaust gas concentrations of O_2, CO_2, and CO measured in low and high frequency acoustic mode tests, respectively. With low frequency pulsations present, only 12% of the injected methanol was burned, and only 5% was burned with high frequency oscillations present. The amount of CO emitted is also much lower with pulsations present than without. The temperatures measured with low frequency oscillations present were approximately 550°f just downstream of the combustor tailpipe and about 350°f at the exhaust entrance, and with high frequency oscillations the temperatures were 510°f just downstream of the combustor tailpipe and 330°f at the exhaust entrance. The reduction in chamber temperature appears to correlate with the reduced incineration efficiency. Because this reduction in chamber temperature is due primarily to increased heat losses to the walls, insulation of the chamber walls may significantly alter the results. Therefore, tests performed in a higher temperature, well-insulated incinerator may show very different results. Another peculiarity with the use of methanol is that it vaporizes at a lower temperature than water. Therefore, the steady burning tests showed that more of the methanol was consumed, even though not all of the water was being evaporated.

In the sucrose tests, a solution 10% $C_{12}H_{22}O_{11}$ by weight in a balance of water, with a net heating capacity of approximately 5600BTU/gal., was sprayed into the incinerator chamber. 5.66 gal./hr. of the mixture were injected. The burner was operated at 270MBTU/hr, with phi = 0.56. No visible flame was observed using the sugar solution. In this case, the incinerator chamber temperatures appeared to be below the ignition temperature of the fuel, and no significant amount of burning was observed with or without acoustic forcing. The exhaust gas concentrations of O_2, CO_2, and CO for typical tests with no acoustic forcing, low frequency forcing, and high frequency forcing are shown in Figs. 42-44. The only observed effect on the emissions is that the CO concentration in the exhaust is approximately 0.2% without acoustic forcing and 0.1% when either low or high frequency oscillations are present. When pure water was injected instead of the sugar solution, the exhaust CO concentration was less than 0.01% with or without acoustic excitation, so the CO is coming from the sucrose.

These tests have clearly shown that high amplitude acoustic forcing greatly affected the characteristics of the model incinerator studied at Georgia Tech. A nominal 50% increase in evaporation rate was observed, despite increased heat losses to the uninsulated chamber walls. Unfortunately, this study failed to prove conclusively whether sludge incineration is enhanced or hindered by the presence of acoustic forcing, because of the large heat losses present in the test incinerator. These heat losses are enhanced by the oscillations, and therefore provide a competing mechanism to the incineration process. While a decrease in the incineration efficiency was observed, it can be argued that this is largely due to the acoustically enhanced heat losses. It is certainly true that the incineration cannot be completed without complete drying of the sludge, and therefore, under proper conditions, an increase in evaporation rate should lead to faster incineration. Further testing will be needed to make an adequate assessment of the impact of pulsations on sludge incineration.

Summary and Conclusions

The objective of this program is to investigate the feasibility and benefits of a novel, compact, shipboard sludge incinerator using pulsating combustion technology. The Navy is seeking technologies that will increase the throughput of its sludge incinerators while minimizing emissions of hazardous pollutants. This project is part of a Navy sponsored program with the goal of developing a actively controlled, pulsating sludge incinerator that aims to simplify current shipboard incinerator design, increase its maximum sludge throughput, reduce emissions and lower fuel consumption.

The first goal of this project was the development of a pulse combustor capable of exciting large amplitude acoustic oscillations in the shipboard sludge incinerator. Two types of pulse combustor designs were investigated for use. One style of pulse combustor investigated was frequency tunable pulse combustors, which allow the operating frequency of the pulse combustor to be adjusted to match a resonant acoustic mode of the incinerator chamber. The second style of combustor investigated were aerodynamically valved, helmholtz combustors that generate high amplitude, low frequency oscillations that can be used to generate a non-resonant oscillation in the incinerator chamber.

Two approaches have been taken in the development of a tunable pulse combustor. In order to show that technology exists to create a mechanically tuned pulse combustor for this application, a natural gas fired, mechanically tuned pulse combustor was constructed. The combustor provides a strong sound source and is capable of operating in the frequency range of the incinerator chamber. A number of problems, however, are associated with this design. First, it does not operate on liquid fuels. Liquid fuel oil can be vaporized and fed as a gaseous fuel into the combustor, but to date, condensation prior to the burning zone has led to fouling problems. Second, in order to achieve the high frequencies necessary to excite resonant acoustic oscillations in the incinerator chamber, the mechanically tunable pulse combustor is limited to about 200MBtu/hr power. Third, the mechanical tuning makes control somewhat difficult in this type of combustors.

A novel pulse combustor that can be used in conjunction with a previously developed fuel actuator system was designed and constructed. The concept behind this device is that a compact

combustor mounted to the wall of the incinerator chamber would be provided with a fuel supply modulated with a frequency and amplitude determined by an electronic control circuit. The resulting oscillatory heat addition would drive acoustic oscillations in the chamber as specified by the Rayleigh criterion. Measured pressure signals fed into the control circuit are processed and used to modulate the fuel flow rate, and the resulting feedback loop would cause the system to resonate. The developed burner head was called the pulsed flame tube driver (PFTD). When this system was attached to the incinerator chamber, however, large amplitude oscillations could not be excited. When the PFTD was mounted on a long, narrow pipe, however, it became naturally unstable at a resonant frequency of the pipe, without the use of the fuel modulation system. Testing of the PFTD mounted on the pipe was used to improve the design of the secondary fuel injection system. In this configuration, the use of the control system could increase the amplitude of pulsations to 150% or reduce them to 25% of the natural instability amplitude. The control system could also be used to force oscillations at off-resonant frequencies, but at greatly reduced amplitudes. The reason that the PFTD cannot drive large amplitude oscillations in the incinerator chamber is still under investigation.

The second approach taken to providing large amplitude velocity oscillations in the shipboard incinerator was the use of a low frequency, aerodynamically valved, helmholtz type pulse combustor to force pulsations in the chamber. The primary advantage of this type of combustor is that previous research has shown them to operate on liquid fuel oils. A single frequency, aerodynamically valved, oil burning pulse combustor was constructed. It has a nominal capacity of 750 MBtu/hr of kerosene type fuel oils, such as JP5. With minor design changes, a burner that can operate at over 1 MMBtu/hr can be readily constructed. As presently configured, the combustor operates at 80 Hz and has an acoustic pressure amplitude of approximately 1.5 PSI RMS, or 174 dB. When attached to the incinerator chamber, it drives oscillations on the order of 150dB in the chamber at the operating frequency of the burner and harmonics of this frequency.

The exhaust of a pulse combustor has been demonstrated to atomize a stream of water with a flow rate equal to that of the current sludge atomizer. The spreading angle of the generated spray was shown to be greater when pulsations were present than when the flow was steady, which suggests that more air is entrained into the pulsed spray. Testing showed that the optimal

location to inject the stream of liquid into the oscillating exhaust is just upstream of the end of the tailpipe. While injection upstream in the tailpipe would allow a greater residence time of the droplets in the hot, oscillating exhaust, several problems exist that make it impractical. Also, coaxial injection appears to provide a more uniform, better-distributed spray pattern than injecting the liquid radially into the exhaust stream.

Pulsed incineration tests were performed using a gas fired burner that could be operated at 80Hz, 240Hz, and in steady state mode. The use of this combustor allowed comparisons to be drawn between different modes of excitation, which could not be achieved using the oil burner. Initial testing showed that the heat losses from the incinerator chamber were greatly increased in the presence of pulsations, and the gas fired pulse combustor was shown to emit roughly 50% less nitrogen oxides when operated in a pulsating mode. Tests to determine whether the maximum evaporation rate of a spray of water into the incinerator chamber would be affected by acoustic oscillations were performed. The results show that, despite increased heat losses and the subsequent lower chamber temperatures, the evaporative efficiency of the incinerator was typically 50% greater when oscillations were excited in the chamber. Tests were also performed in which methanol and sugar solutions were used as liquid waste surrogates. In these tests, the performance of the incinerator was observed to be better without pulsations. This was believed to be due to the lower incinerator temperatures in the acoustic tests, which prevented ignition of the surrogate wastes. Additional testing needs to be performed in an incinerator in which heat losses to the walls can be minimized, so that the competing effect of acoustic heat transfer to the walls of the chamber can be eliminated before any conclusions about the effect of pulsations on the overall incineration efficiency can be drawn.

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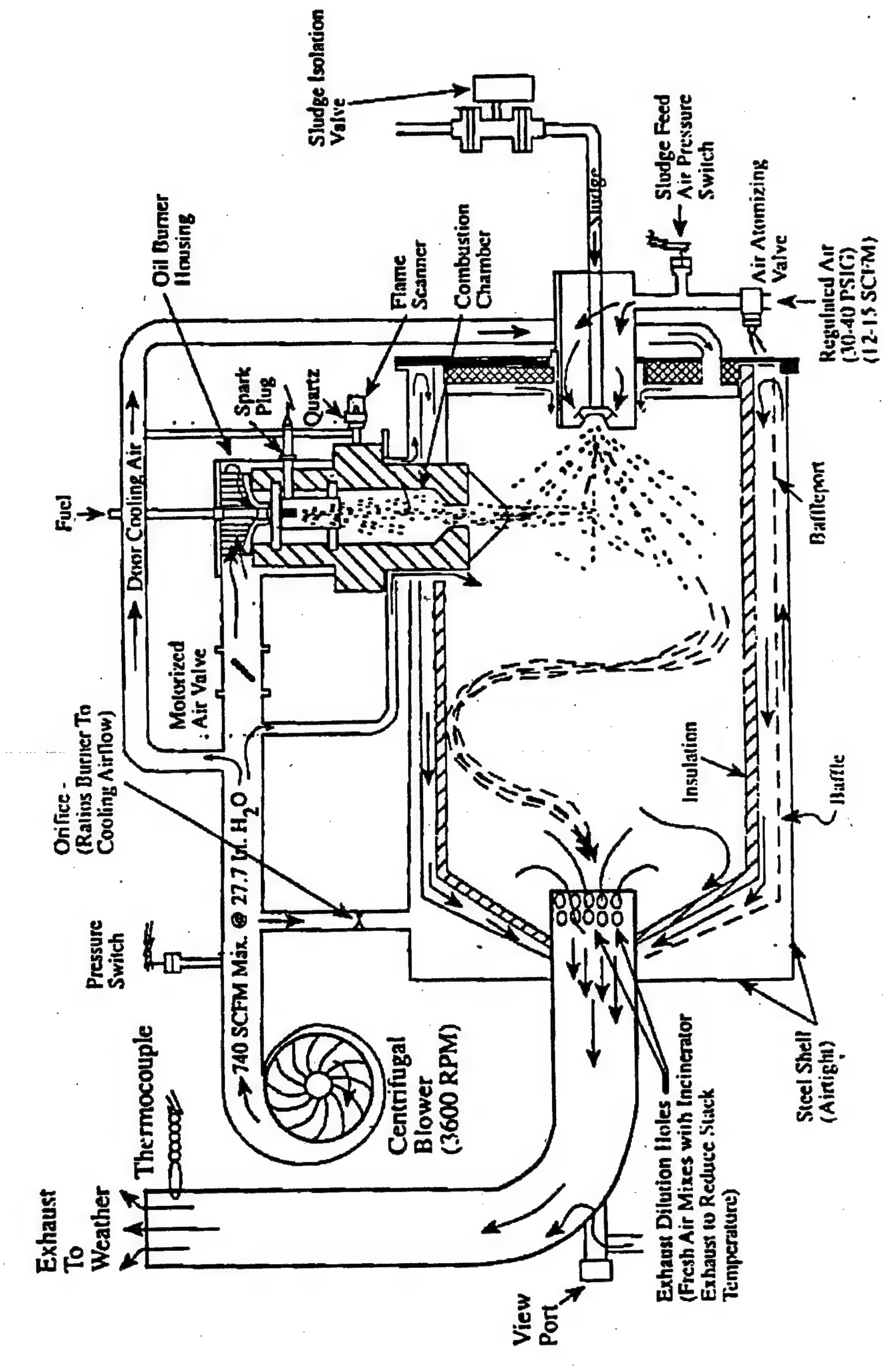


Fig. 1 - Schematic of the current generation shipboard sludge incinerator.

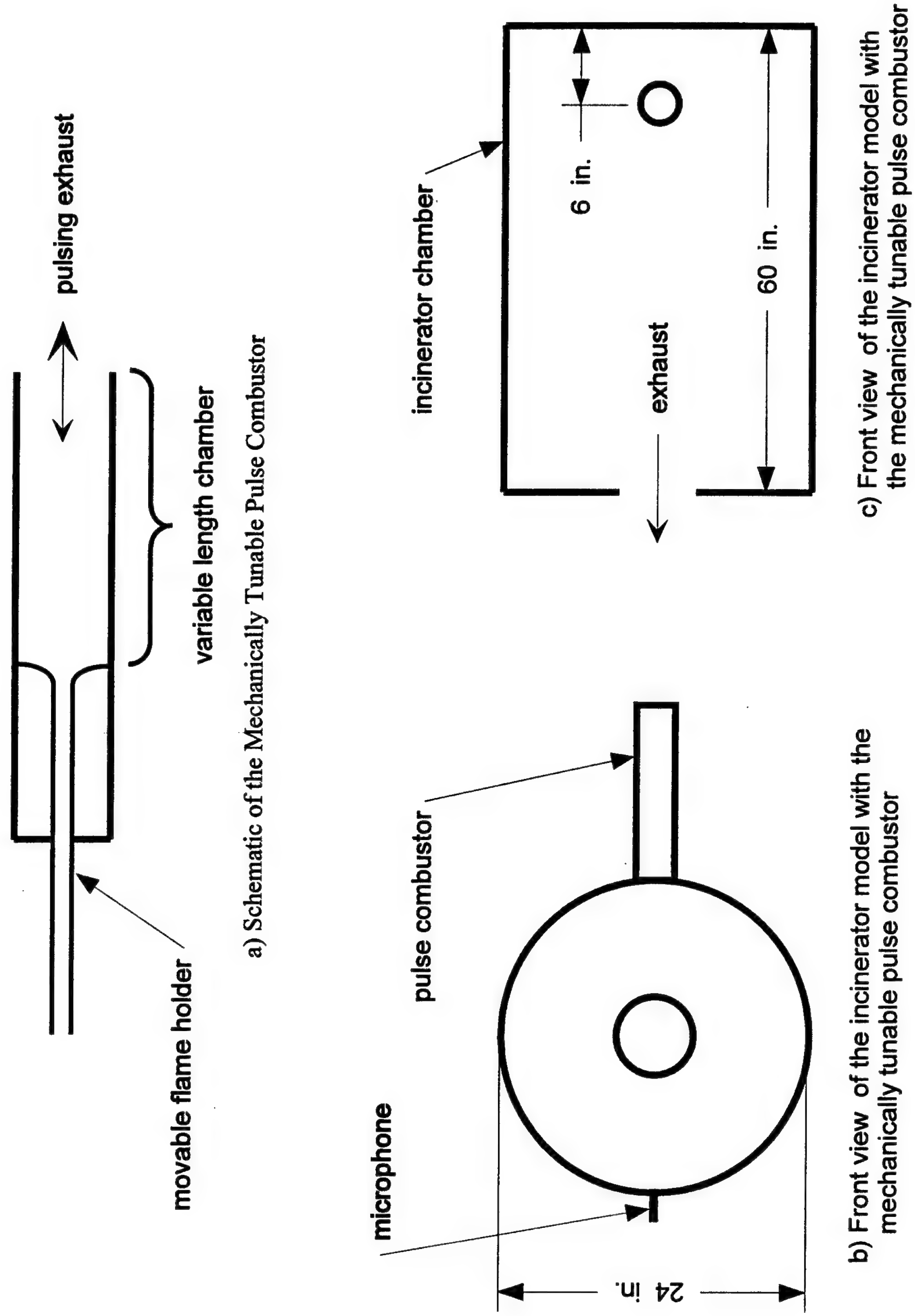


Fig. 2 - The mechanically tunable pulse combustor and the model incinerator

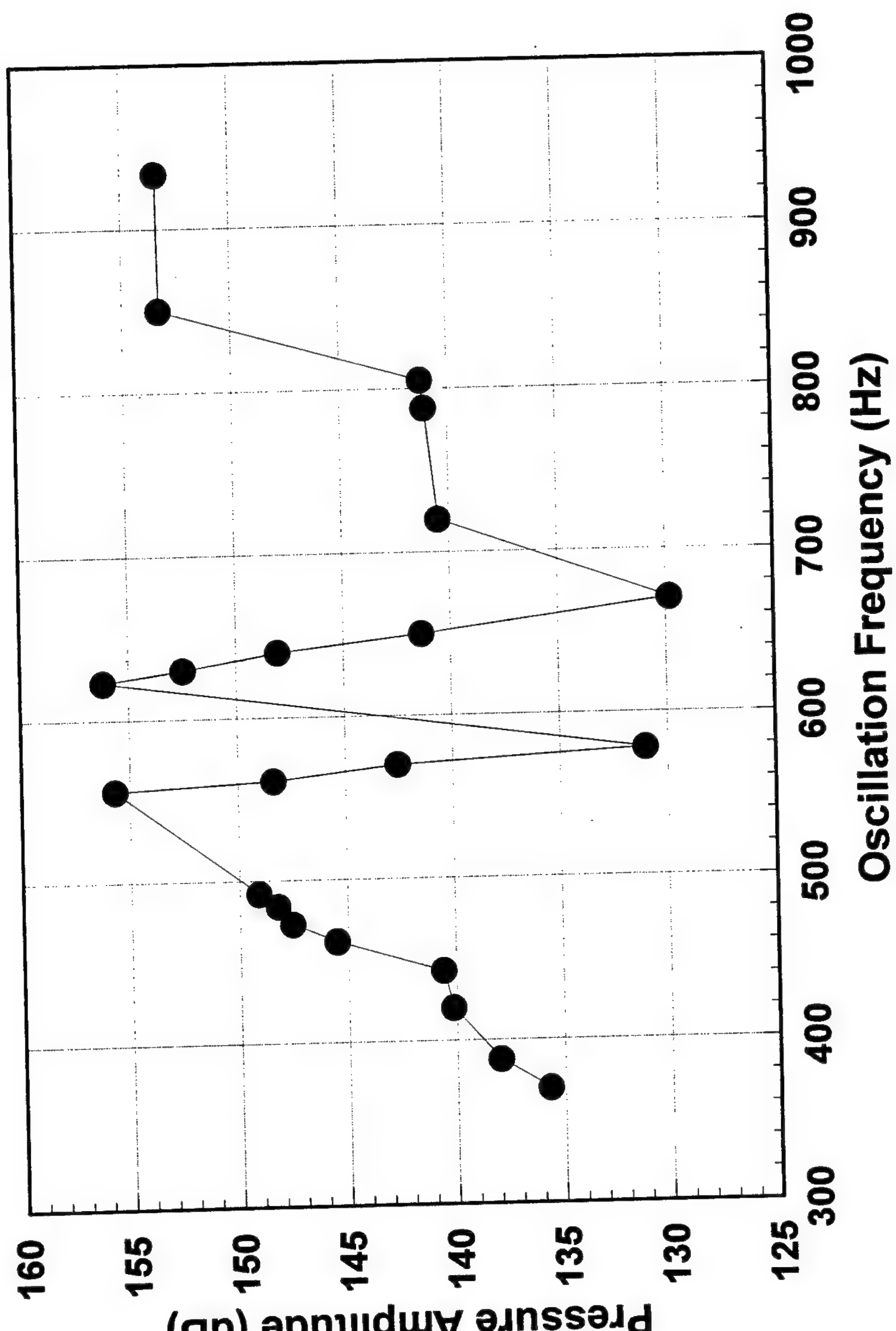


Fig. 3 - Pressure amplitudes excited in the model incinerator using the mechanically tunable pulse combustor

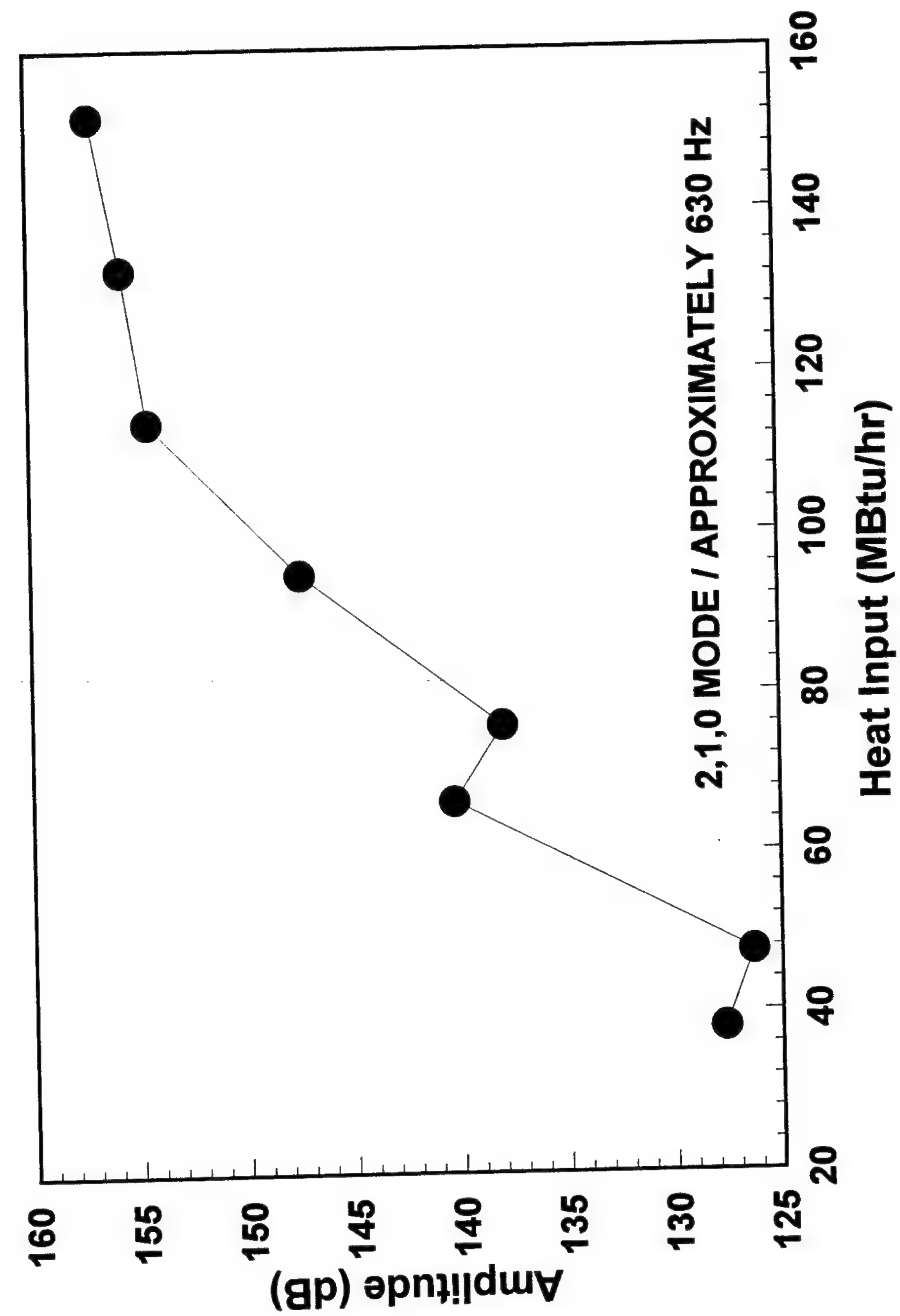


Fig. 4 - Correlation of amplitude in the incineration chamber to the fuel input of the mechanically tunable pulse combustor

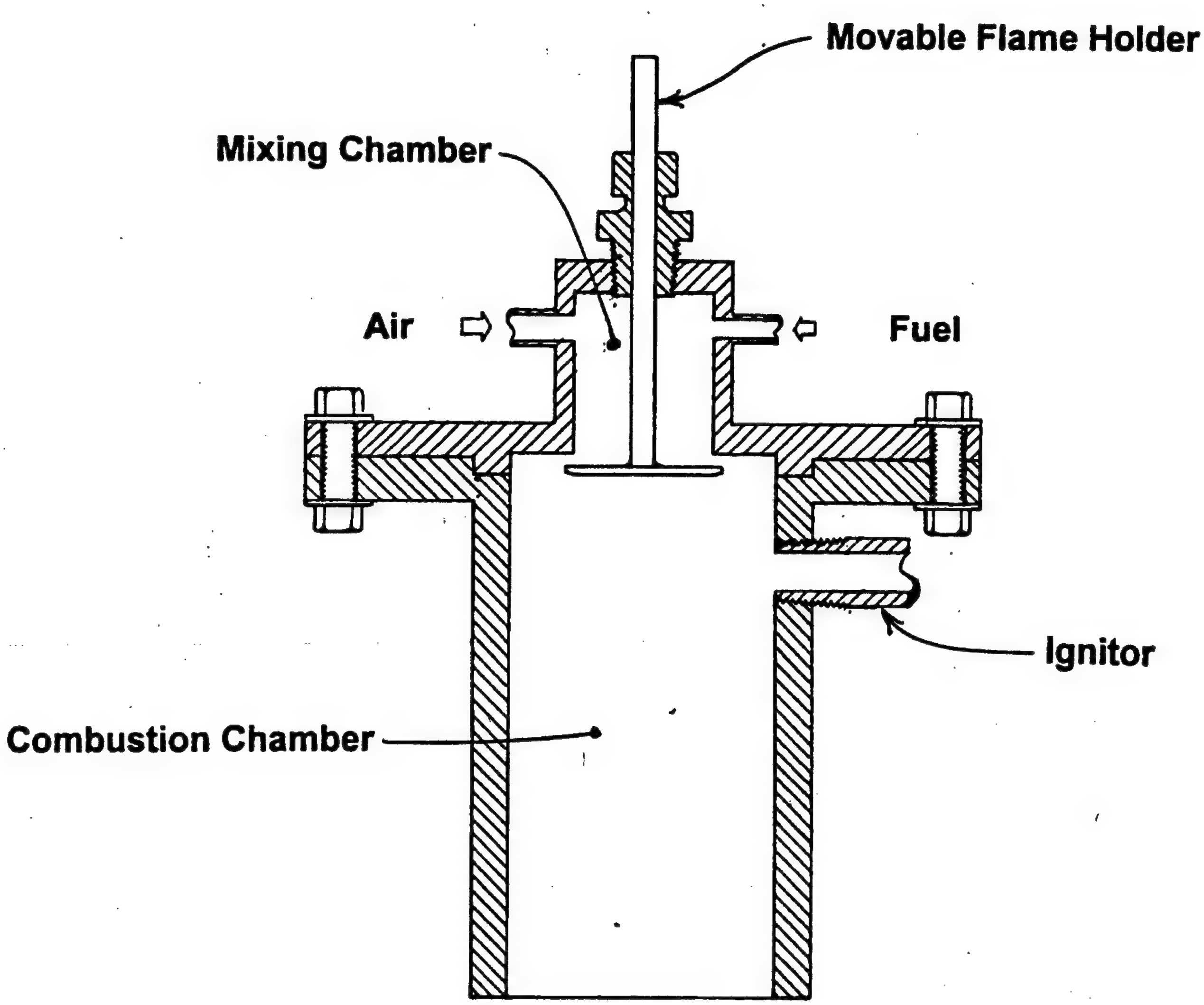


Fig. 5 – A schematic of the PFTD configured without the secondary fuel injector and actuator.

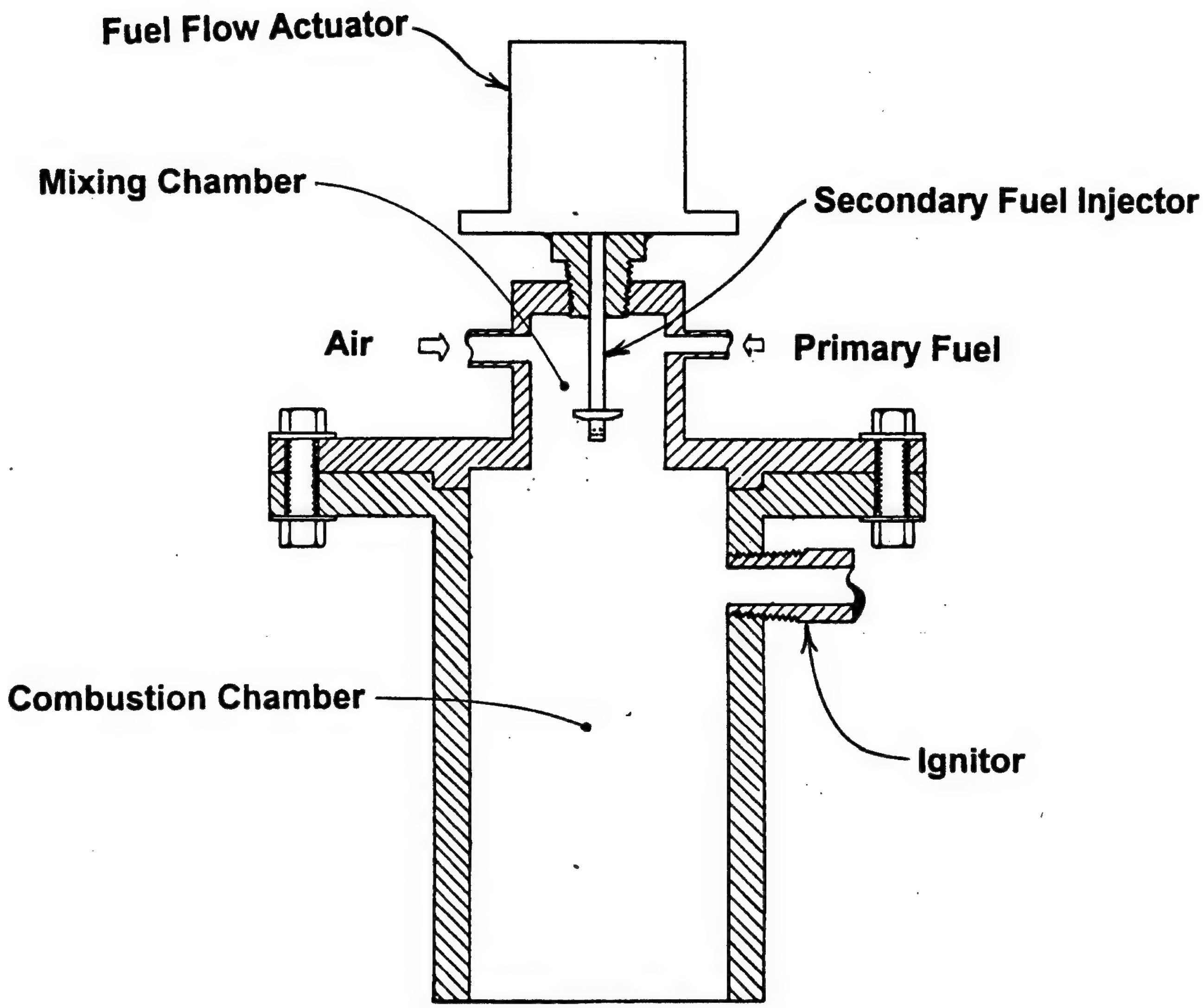


Fig. 6 – A schematic of the PFTD configured with the secondary fuel injector and actuator installed.

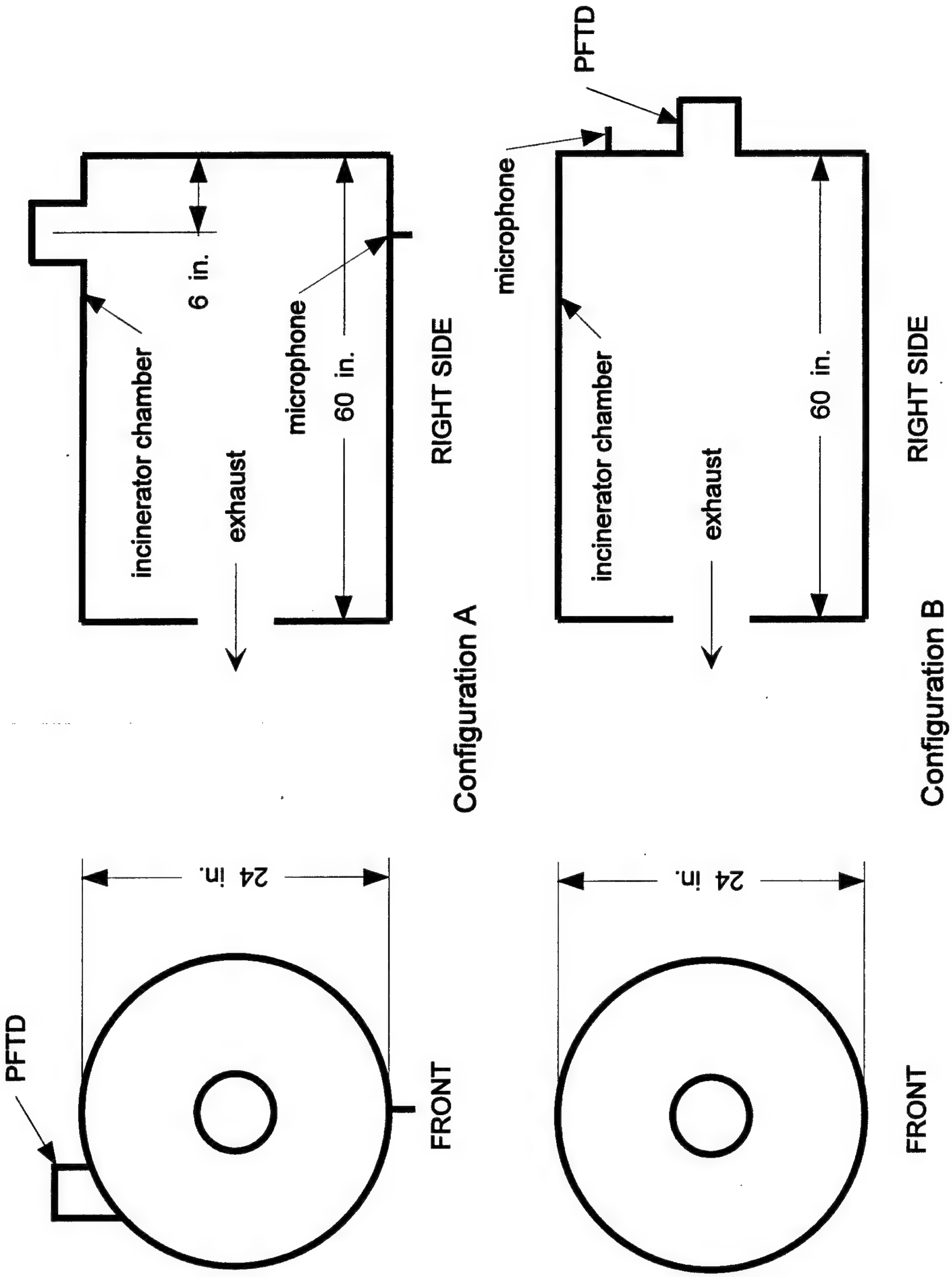


Fig. 7 - Configurations of pulsed flame tube driver on the incinerator chamber

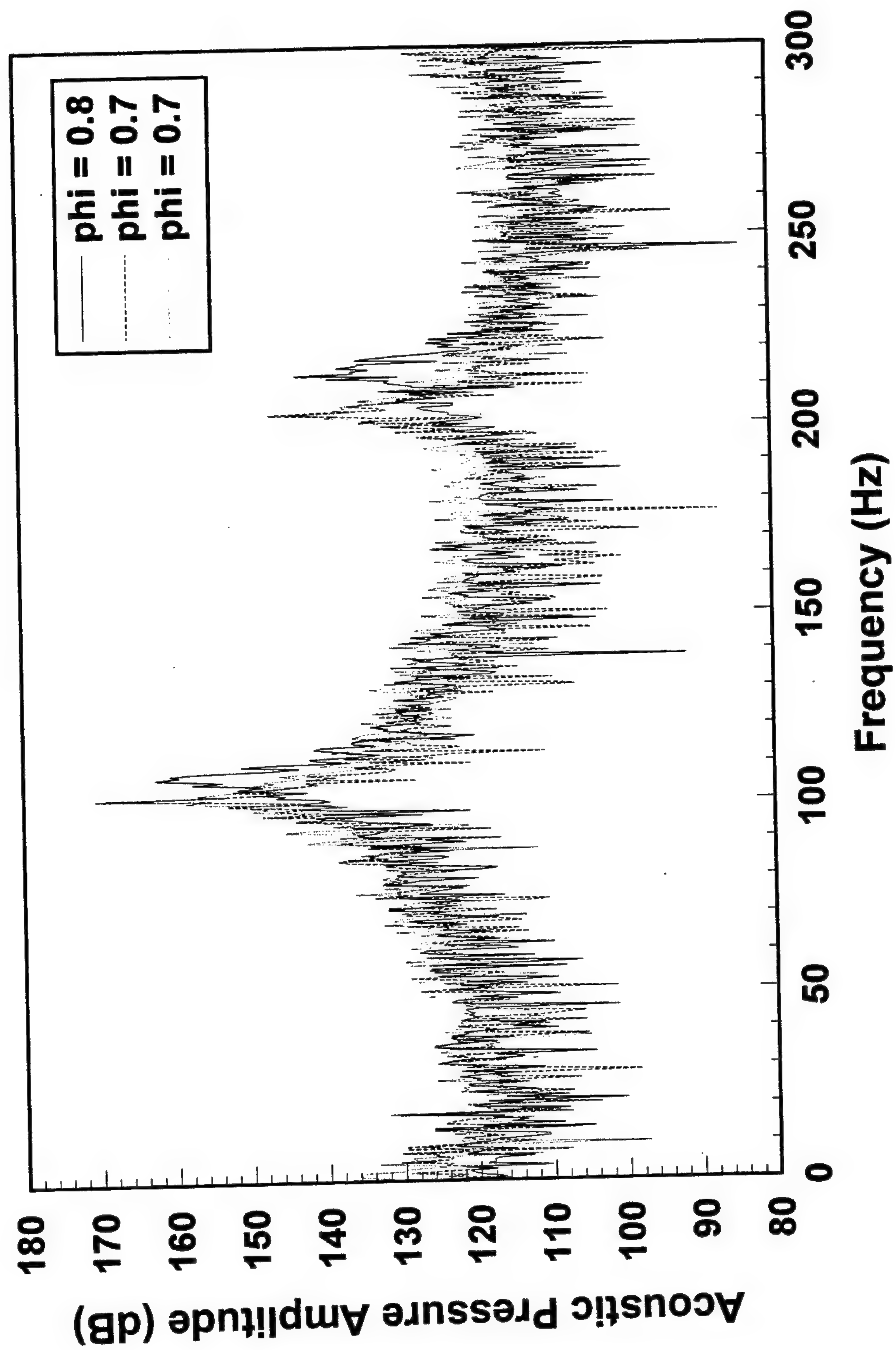


Fig. 8 - Self-excited oscillations driven by the PFTD in a 51" long pipe

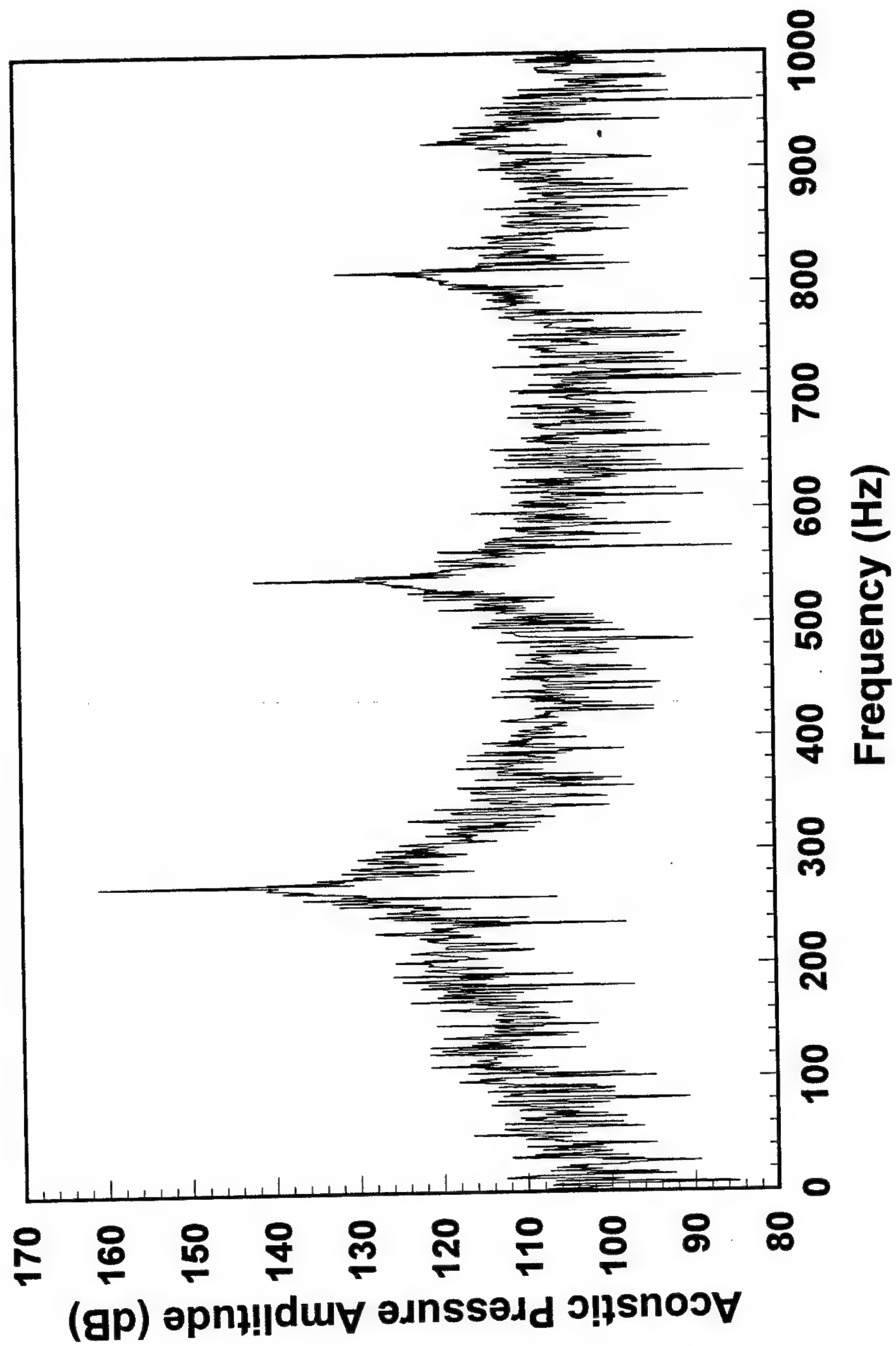


Fig. 9 - Acoustic pressure forced in an 18 in. long resonator pipe using the PFTD and closed loop active control.

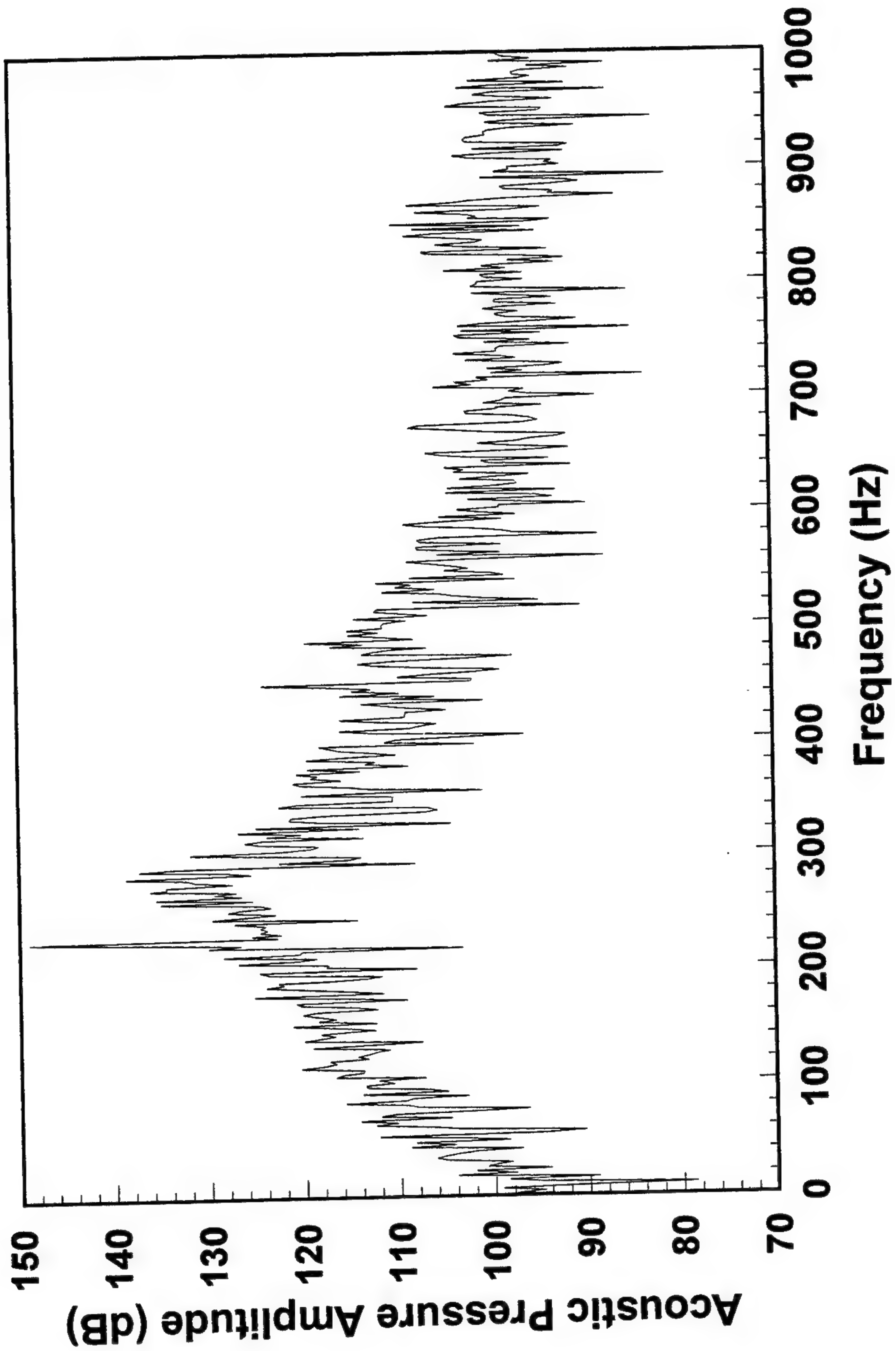


Fig. 10 - Example of secondary fuel injection at an off-resonant frequency in which the injection occurred at 220 Hz, while the quarter wave resonance frequency is approximately 300 Hz.

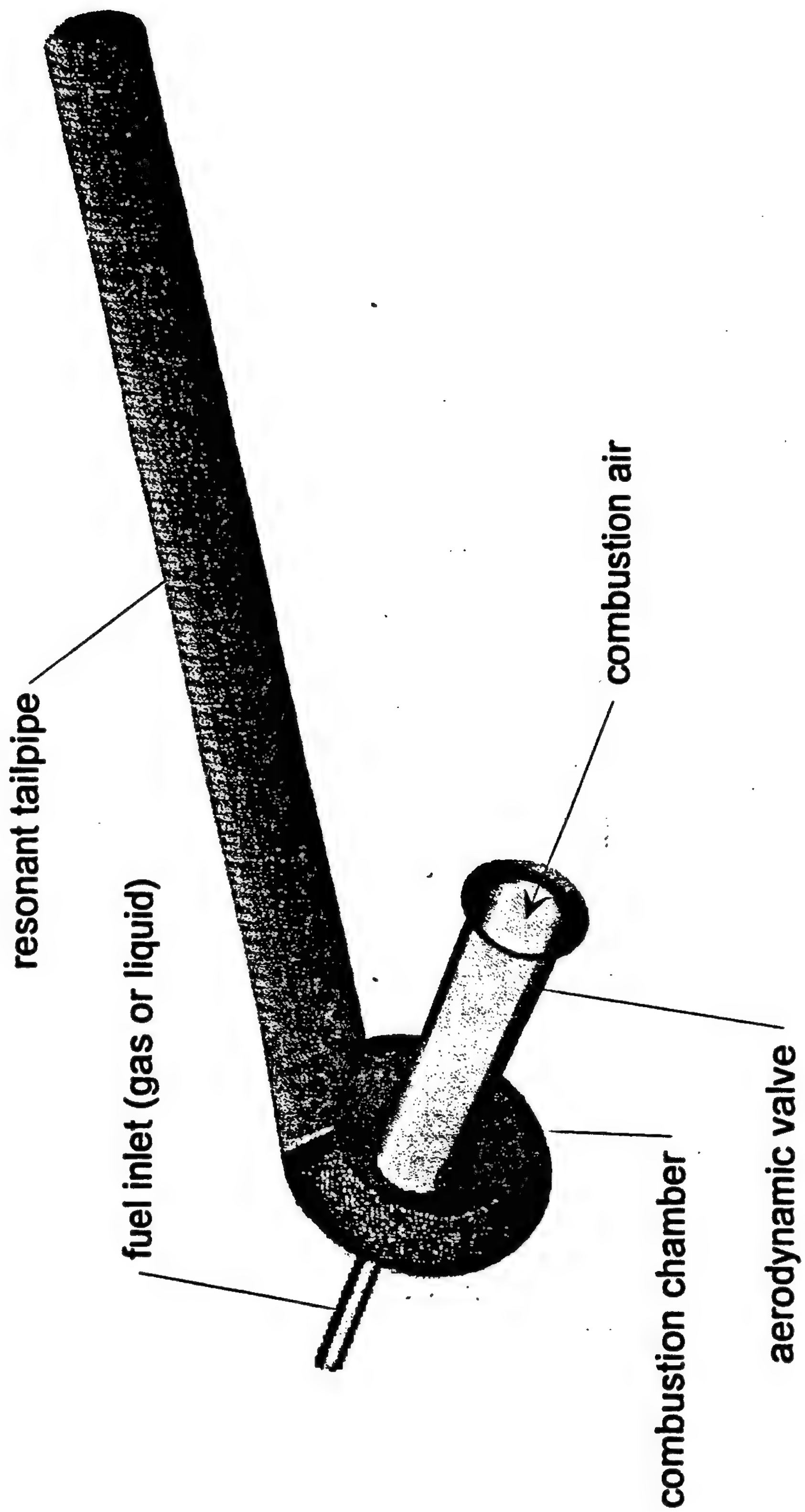


Fig. 11 – Rendering of the oil burning, single frequency pulse combustor.

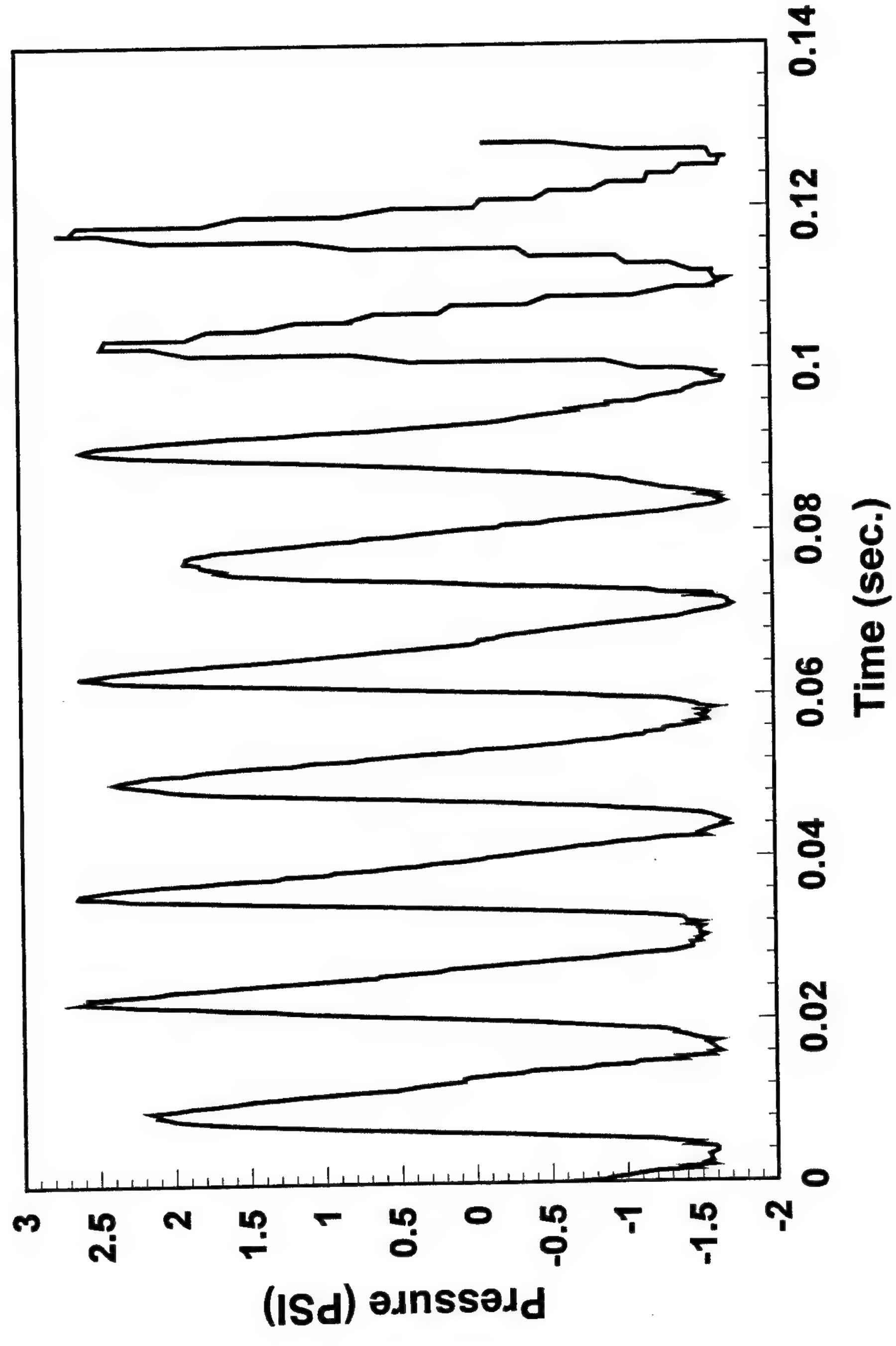


Fig. 12 - Time trace of the acoustic pressure in the combustion chamber of the oil burning pulse combustor.

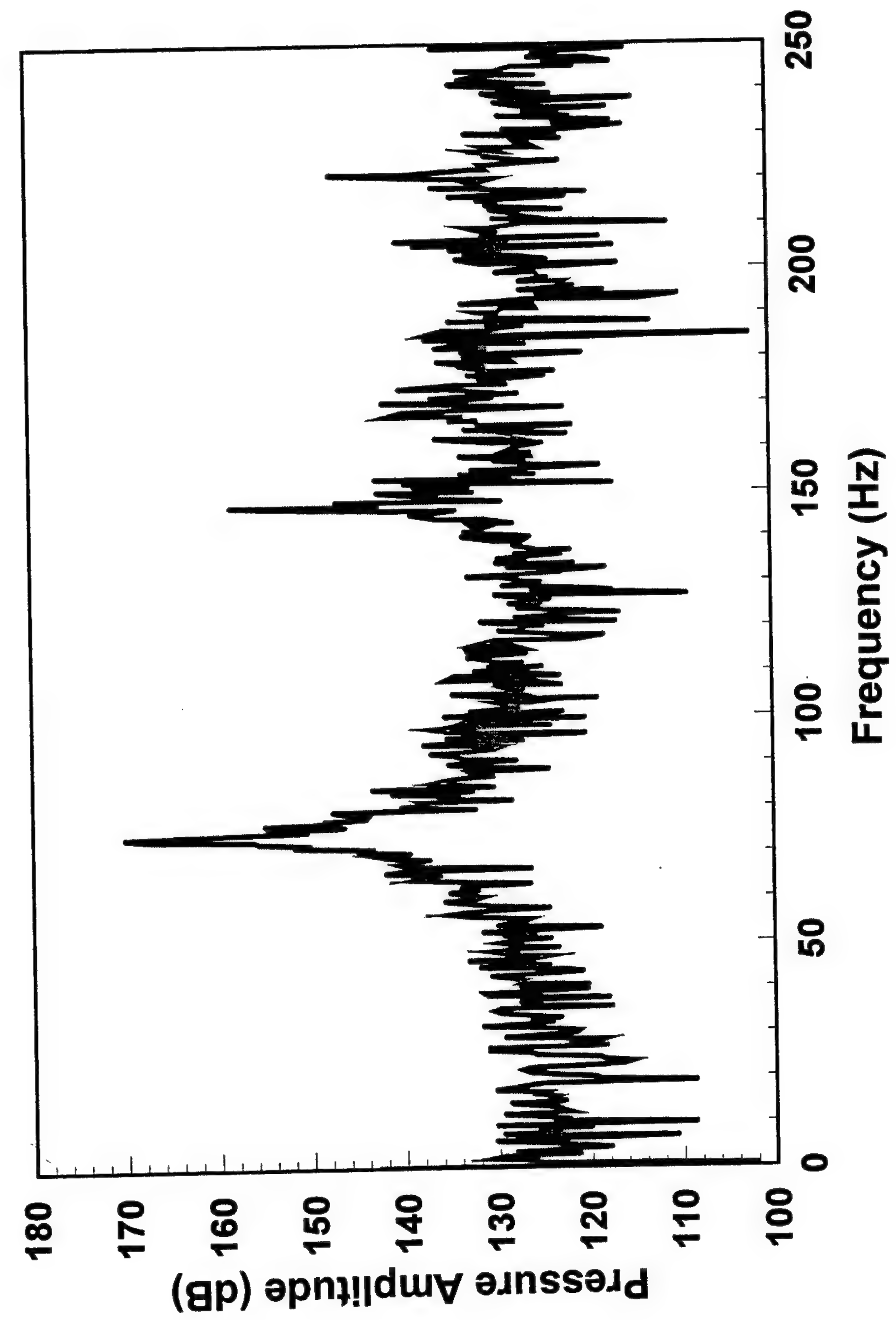


Fig. 13 - Autospectrum of the acoustic pressure in the combustion chamber of the oil burning pulse combustor.

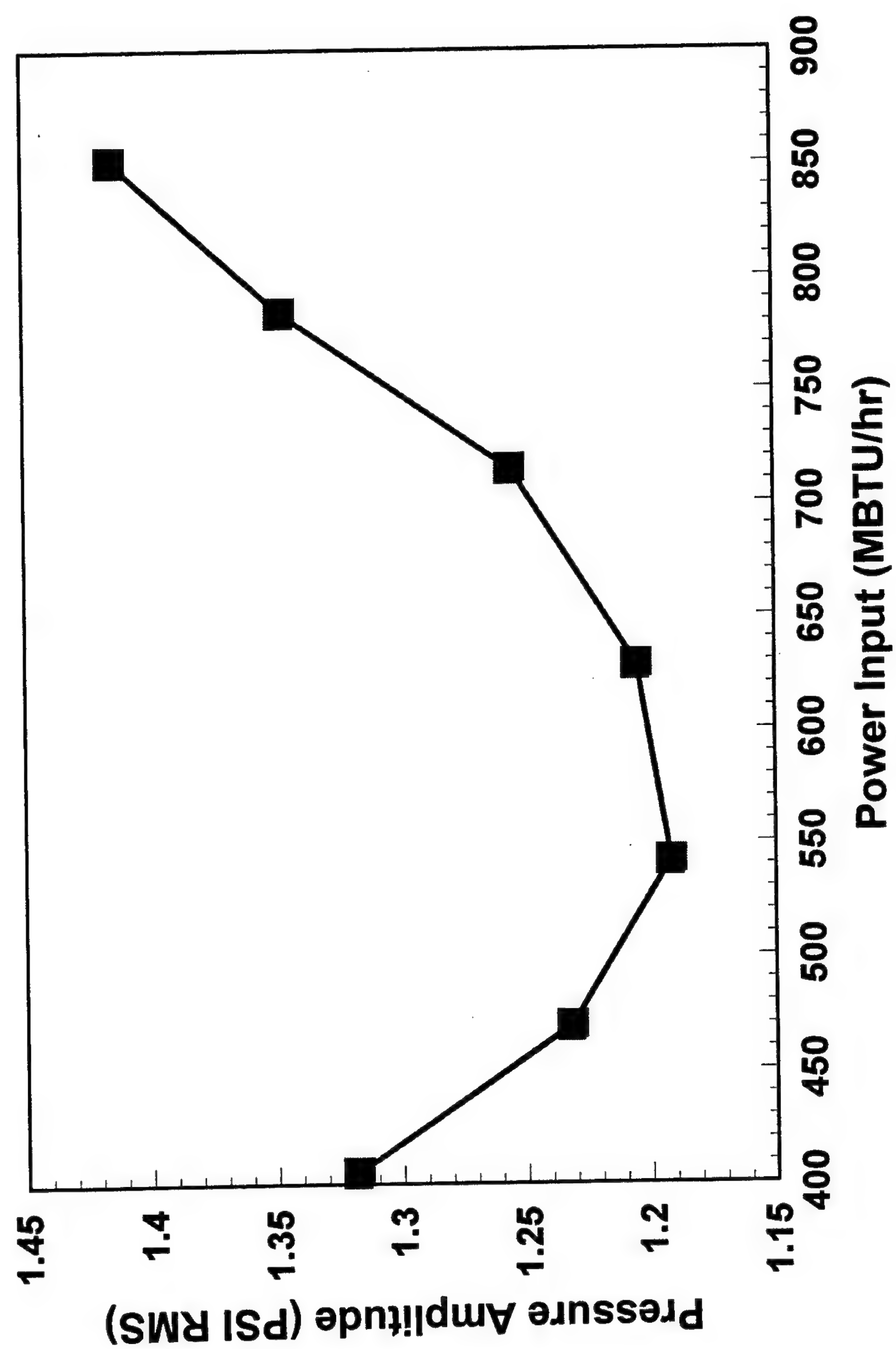


Fig. 14 - Acoustic pressure amplitude in the combustion chamber for different fuel input rates.

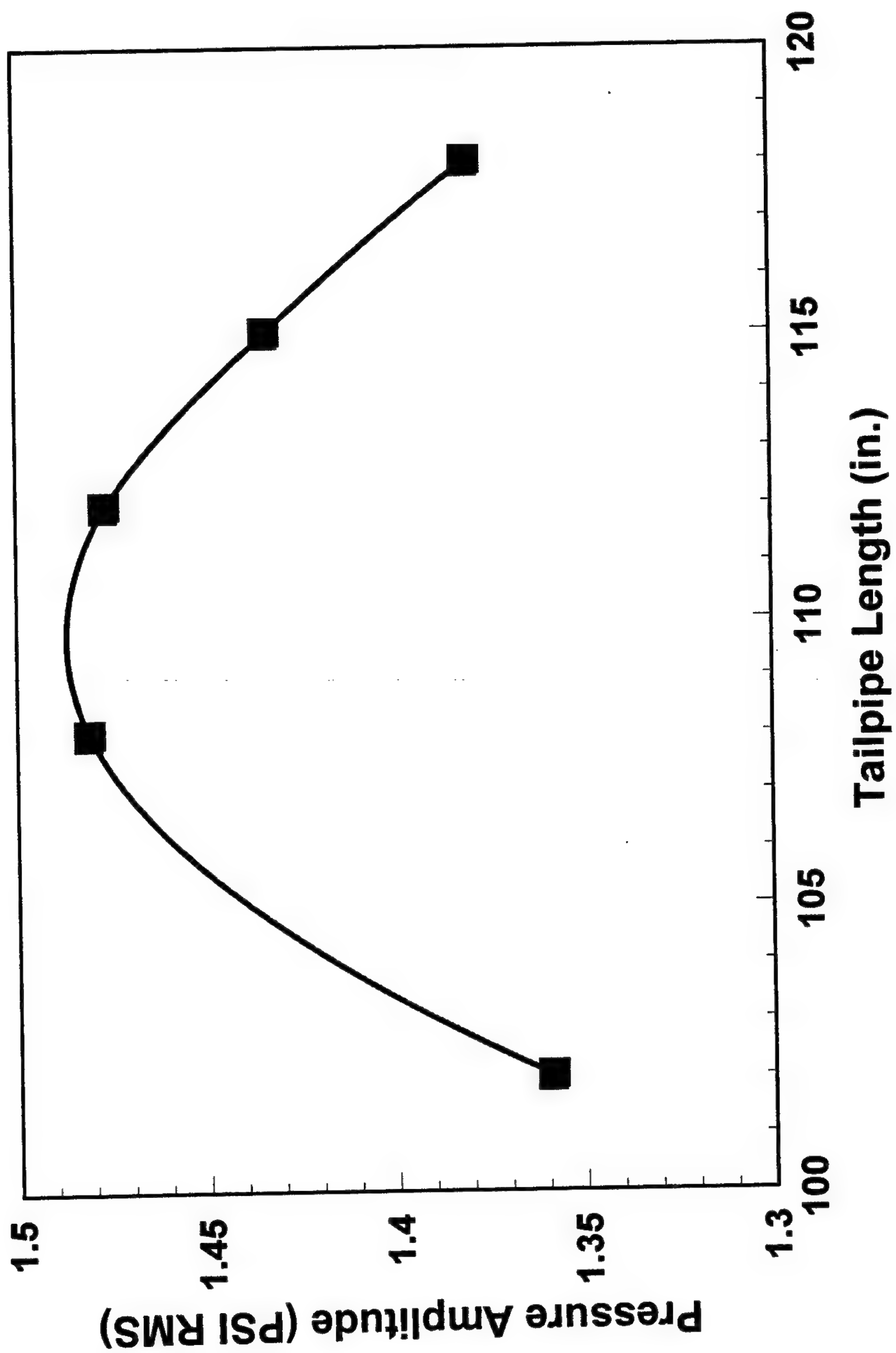


Fig. 15 - Acoustic pressure amplitude in the combustion chamber for various tailpipe lengths.

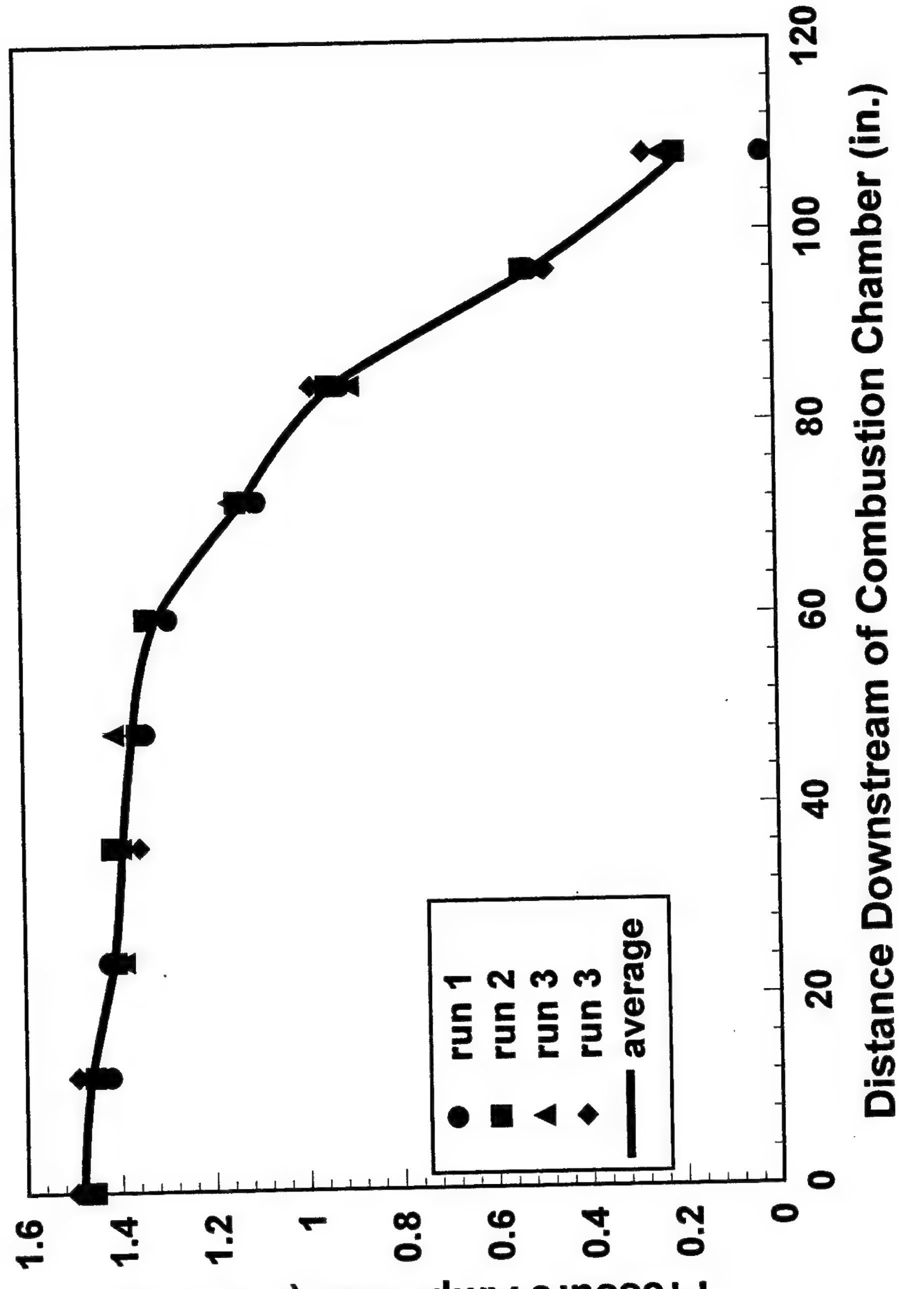


Fig. 16 - Acoustic pressure amplitude measured along the pulse combustor tailpipe..

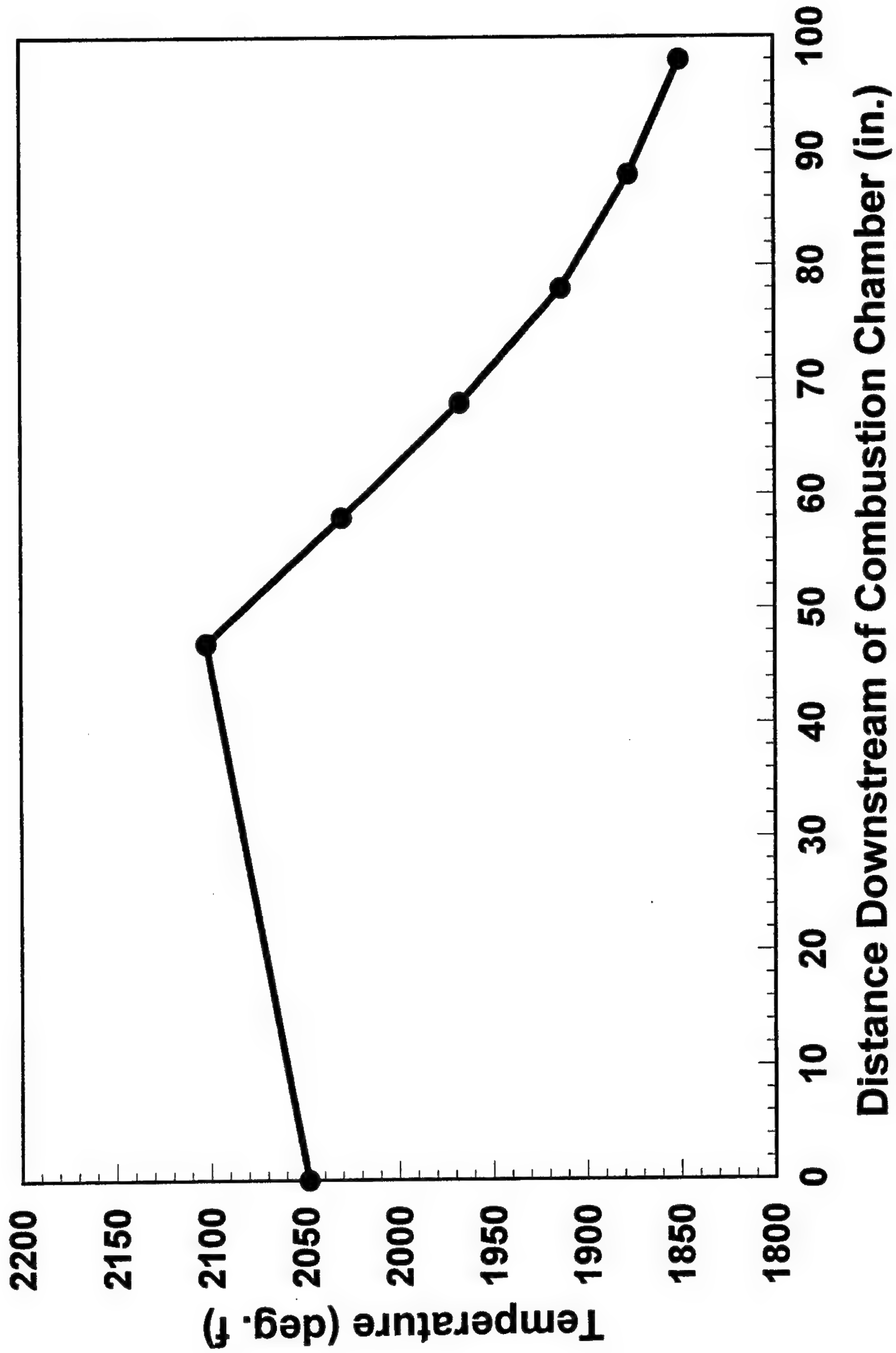


Fig. 17 - Mean temperature measured along the centerline of the oil burning pulse combustor tailpipe.

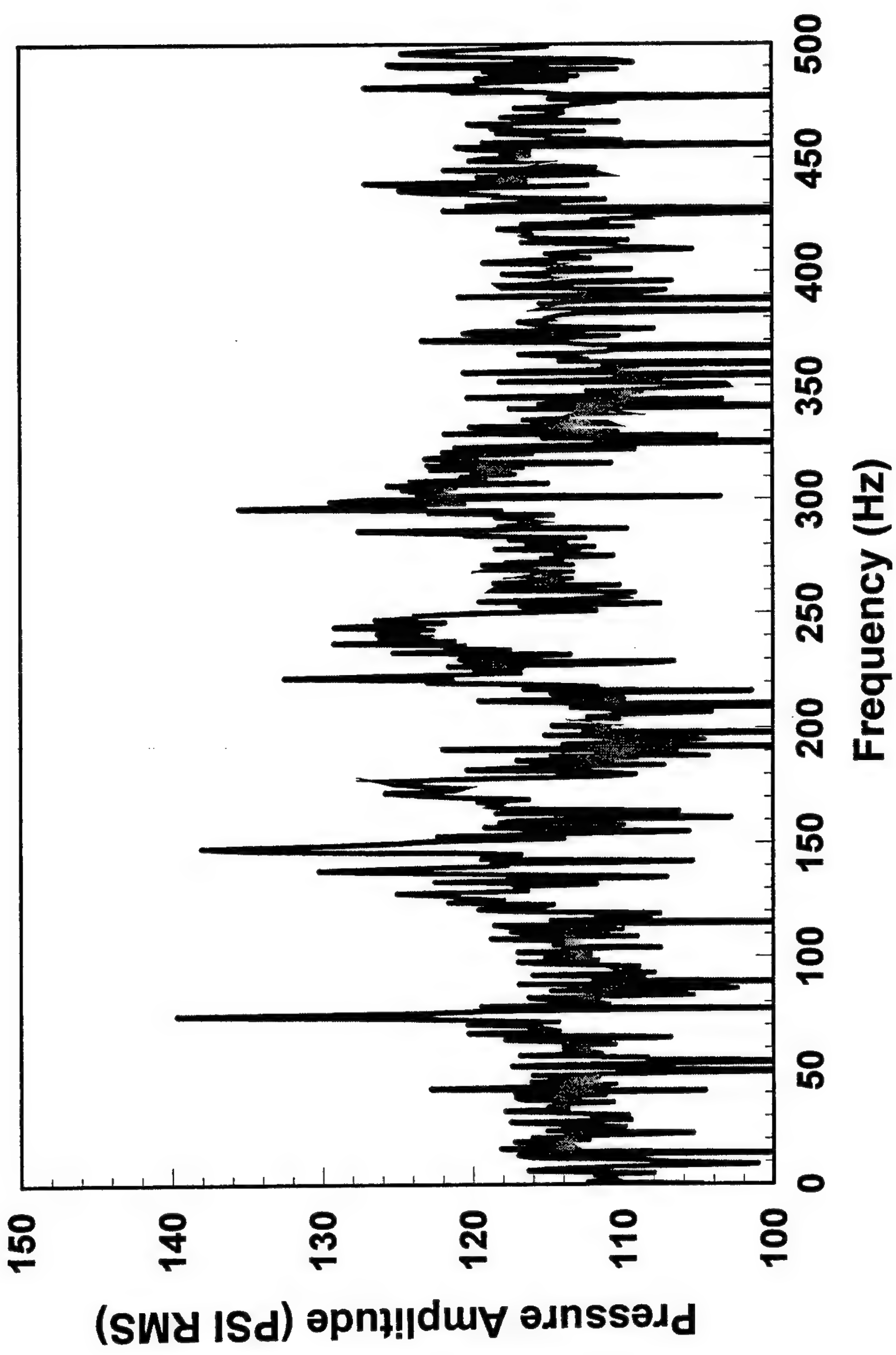


Fig. 18- Autospectrum of the acoustic pressure measured at the head end of the incinerator chamber.

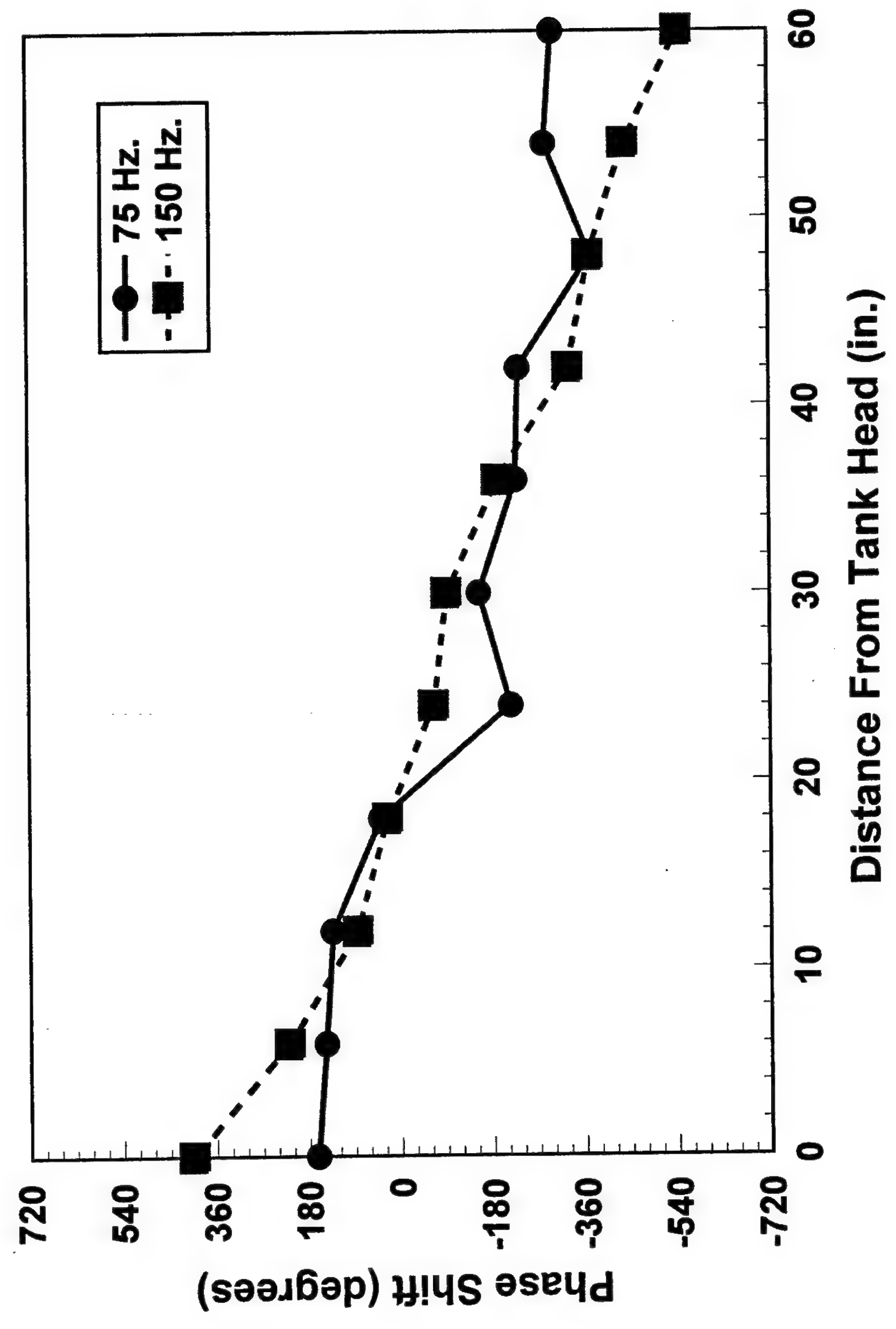


Fig. 19 - Phase shift between the first two modes in the incinerator chamber and the combustor pressure oscillation.

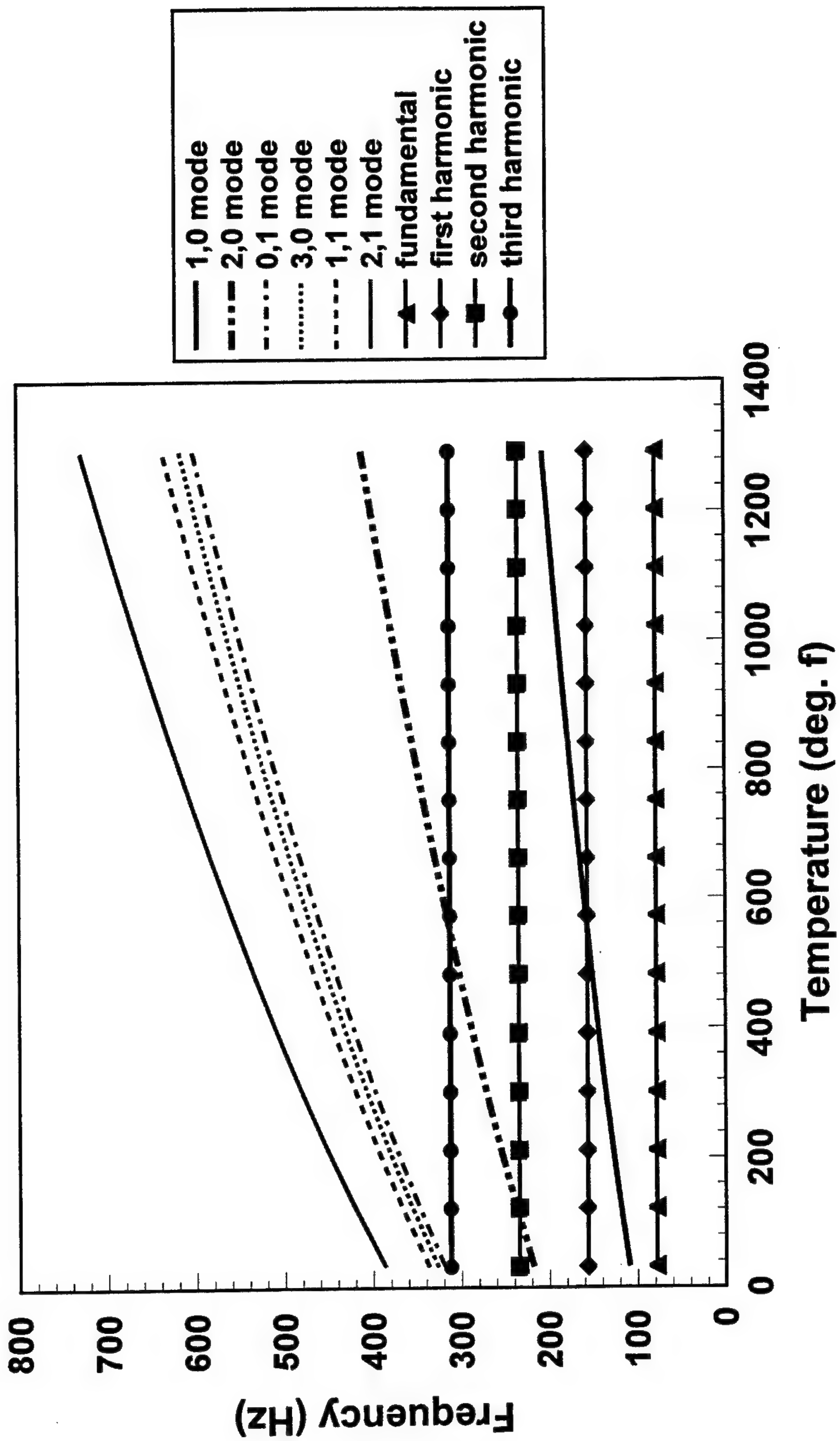


Fig. 20 - Comparison between the resonant acoustic modes of the incinerator chamber and the frequencies forced by the pulse combustor.

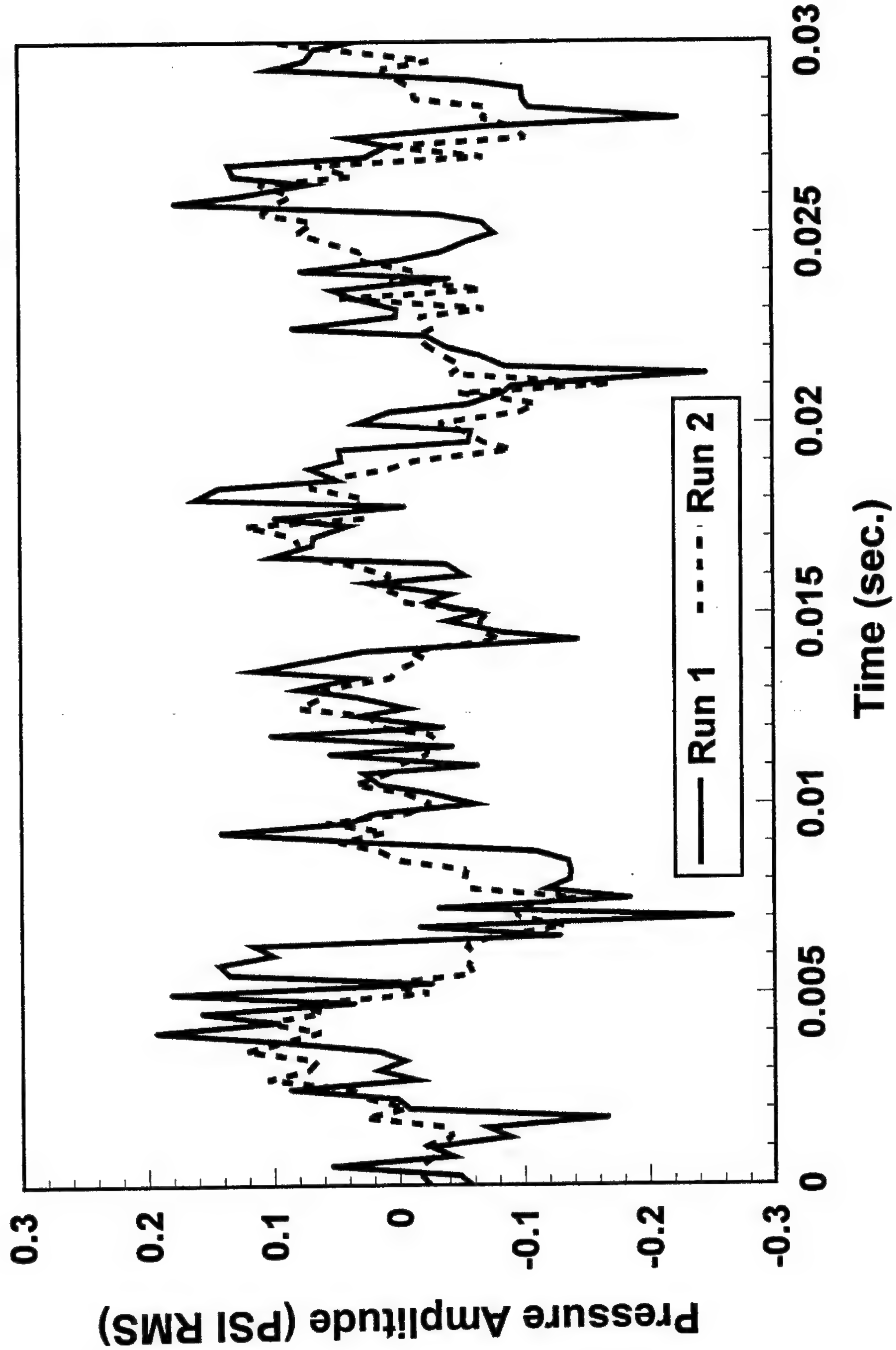


Fig. 21 - Two time traces of the acoustic pressure measured at the head end of the incinerator chamber at different average temperatures..

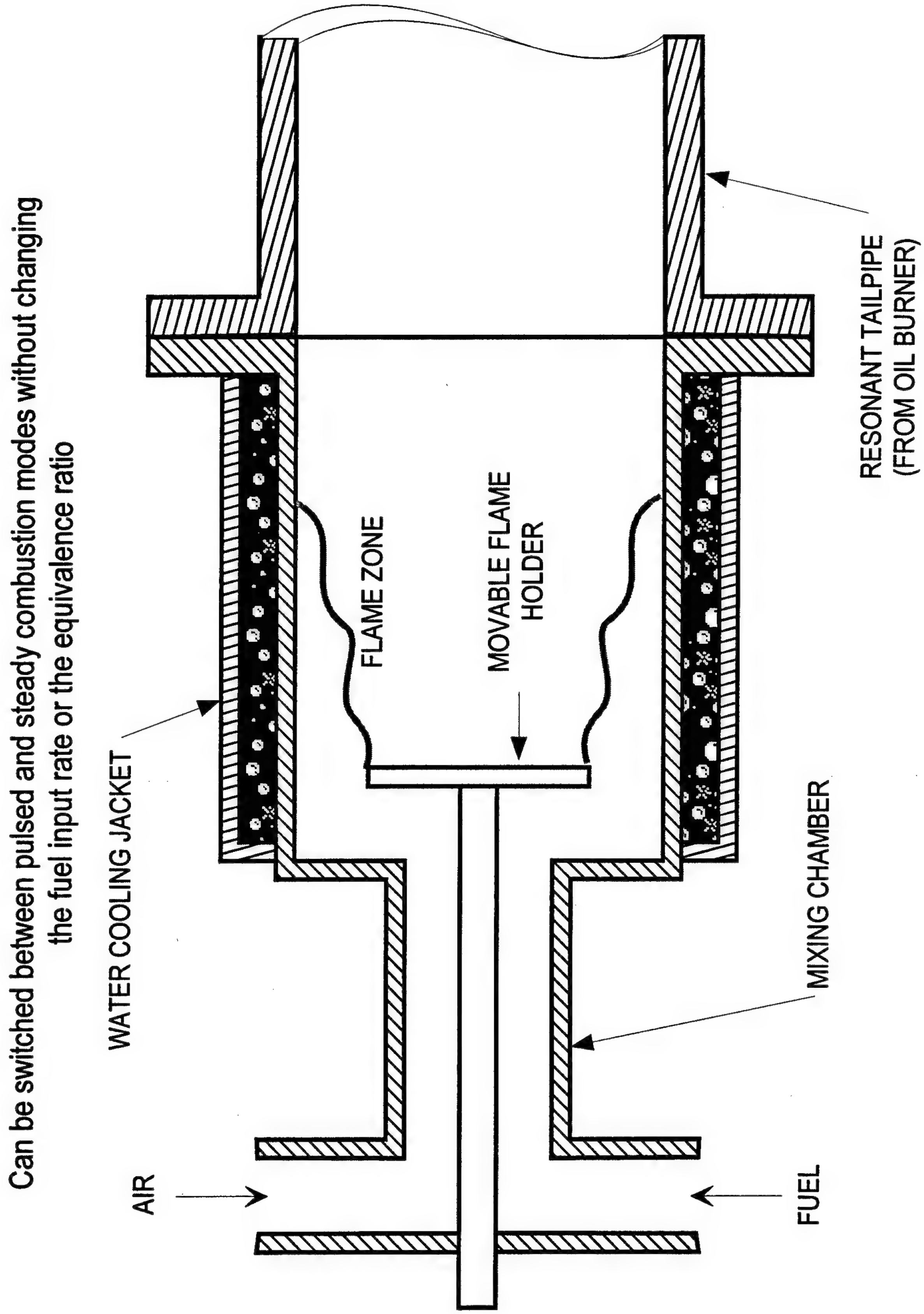


Fig. 22 - Schematic of the gas-fired pulsed combustor used for incineration testing.

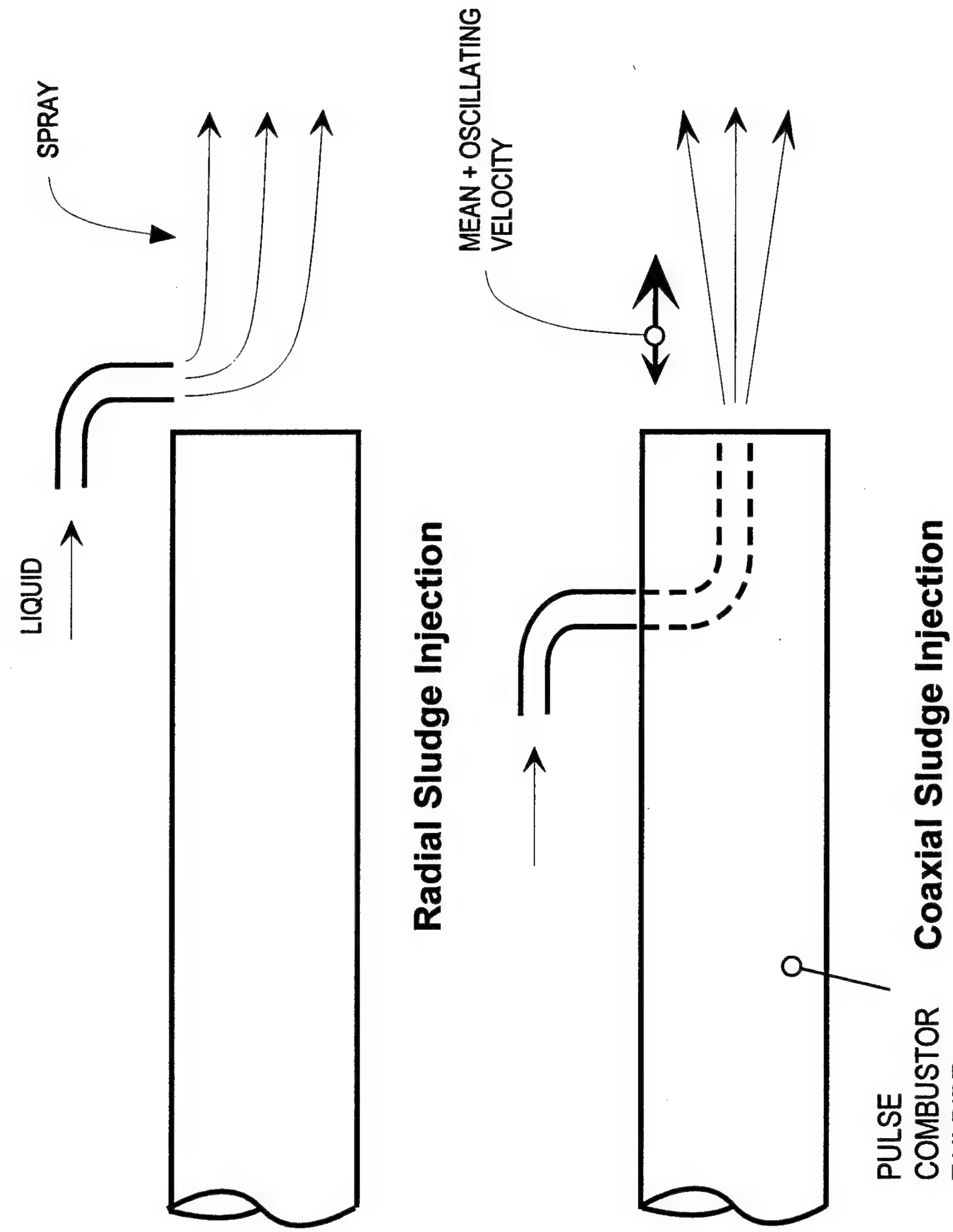
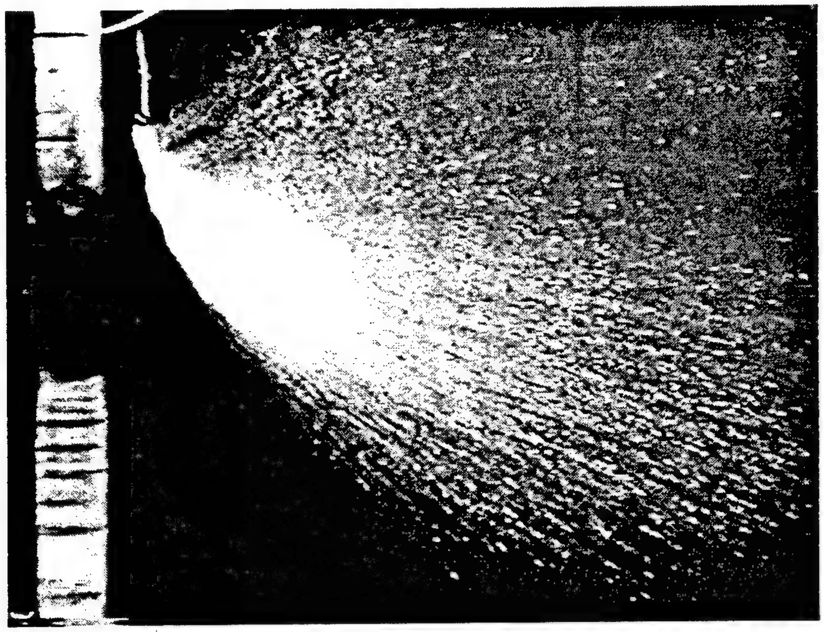
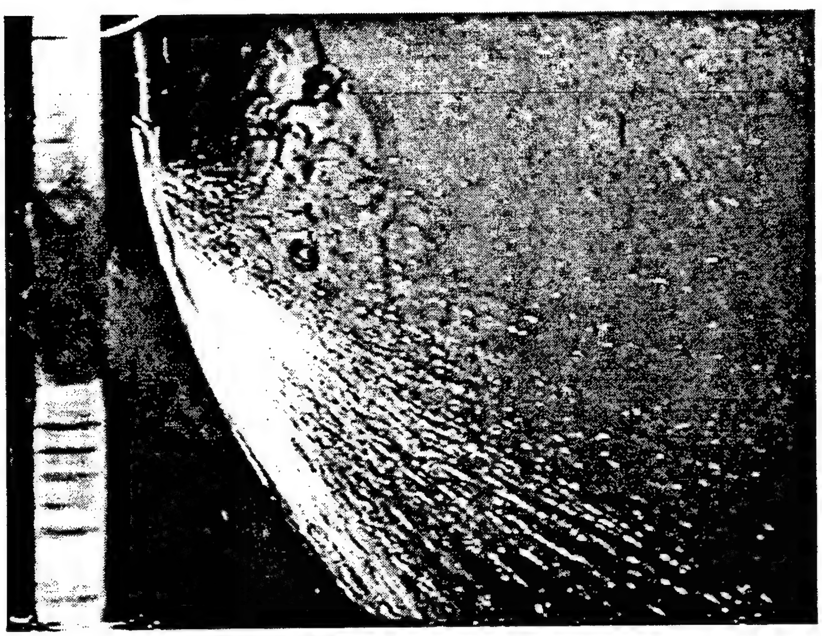


Fig. 23 - Schematic of the atomization test setup showing the orientation of the sludge injection into the pulse combustor tailpipe.

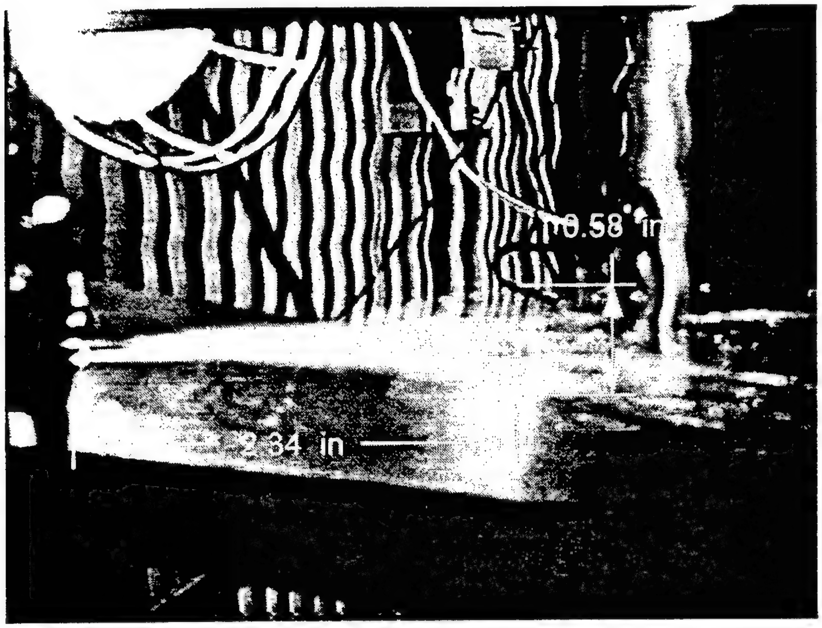


A) PULSATIONS PRESENT

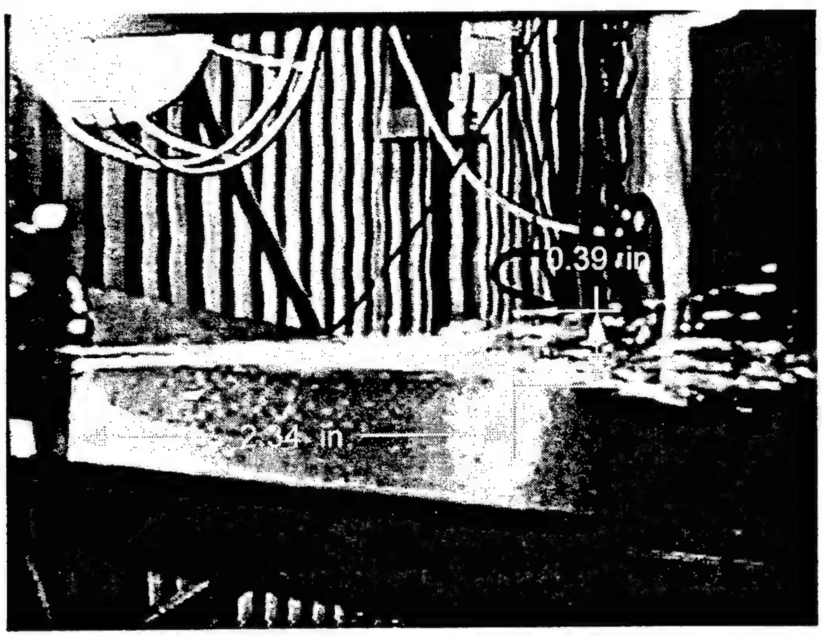


B) NO PULSATIONS

Fig. 24 - Combustor atomization of a radially injected 0.5 GPM water stream with and without pulsations



A) PULSATIONS PRESENT



B) NO PULSATIONS

Fig. 25 - Combustor atomization of a coaxially injected 0.25 GPM water stream with and without pulsations.

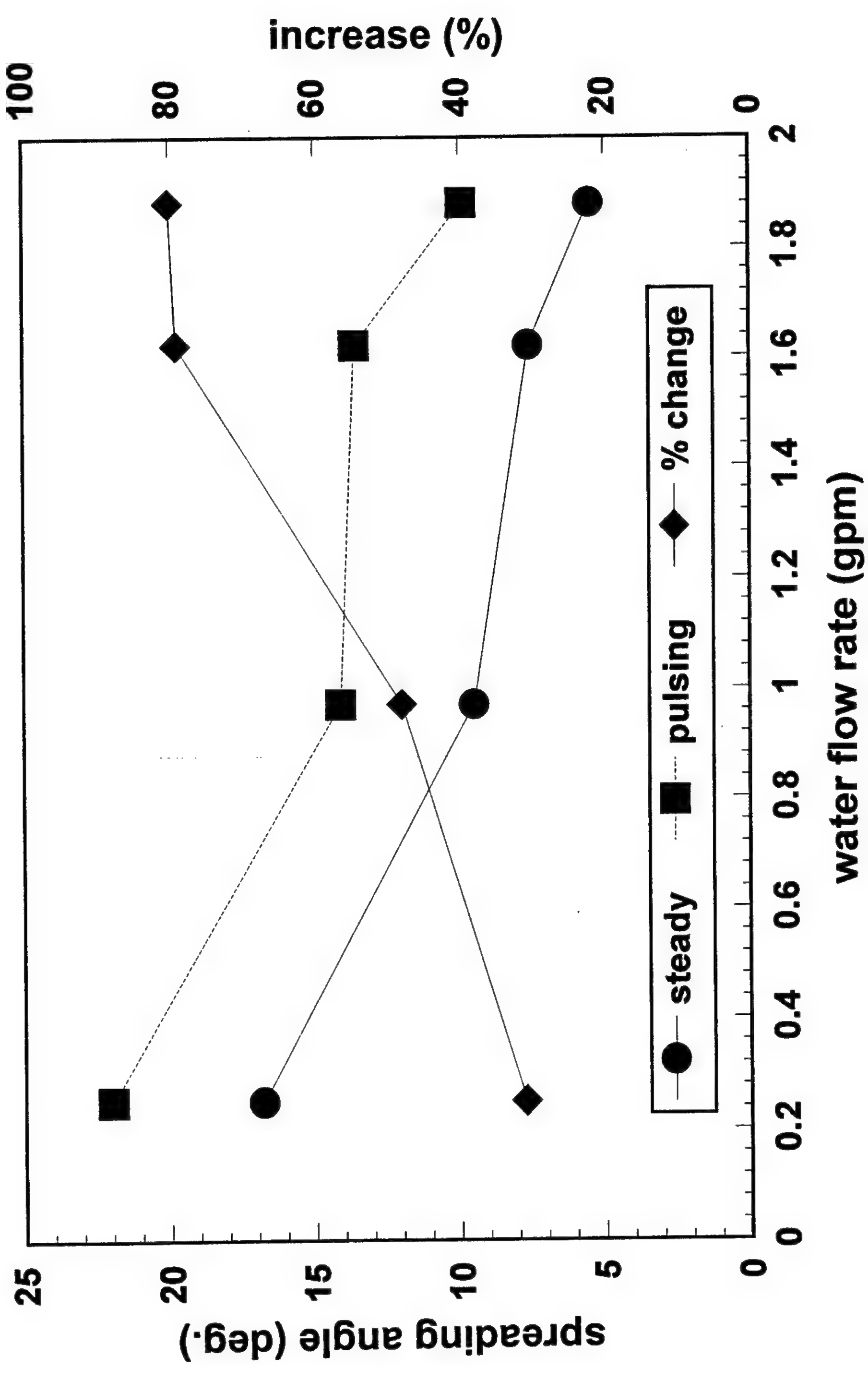


Fig. 26 - Coaxial flow spray enhancement using a 150MBtu/hr tunable pulse combustor.

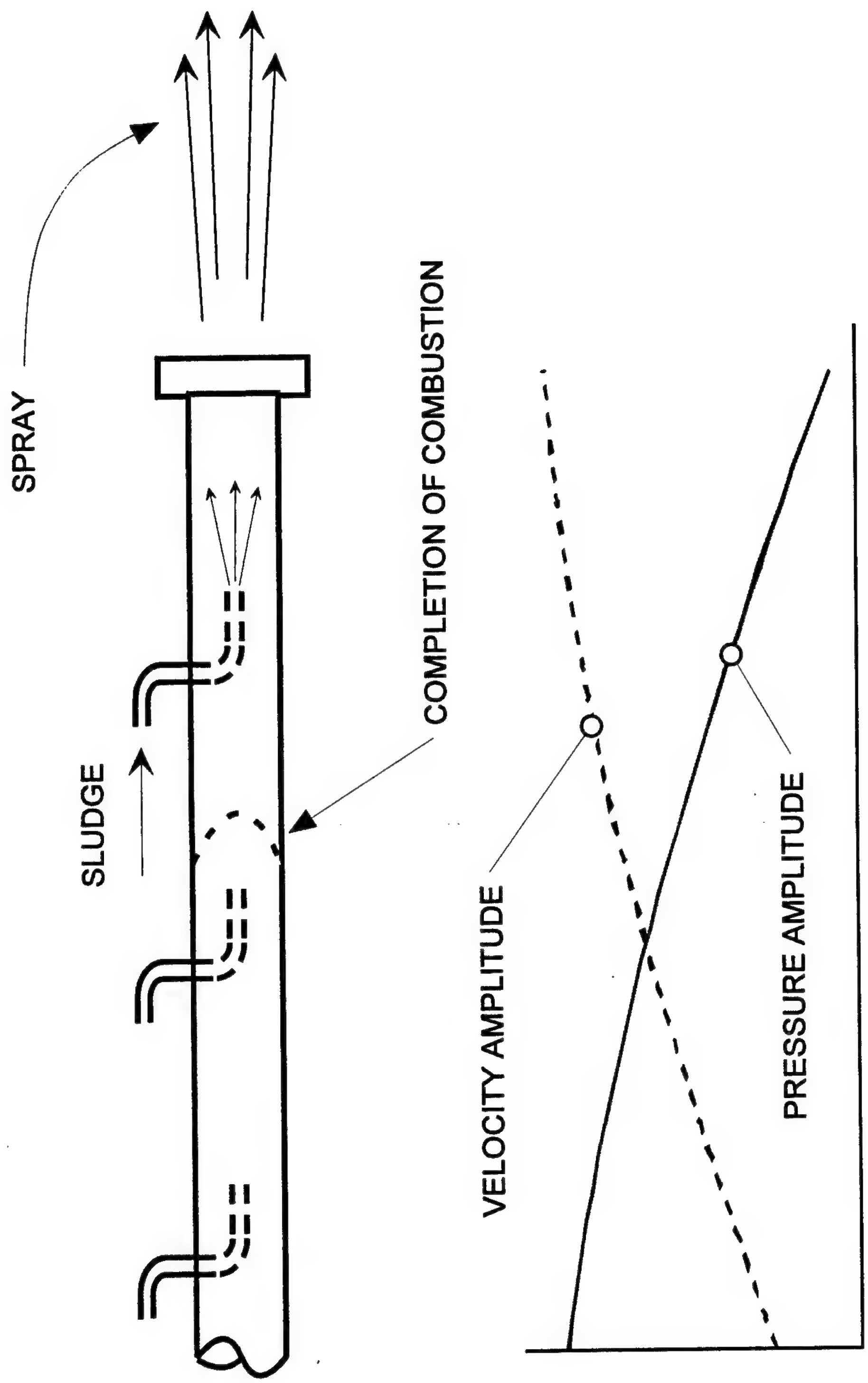


Fig. 27 - Schematiic of the positions and orientations of liquid injection tested in the oil burning pulse combustor tailpipe.

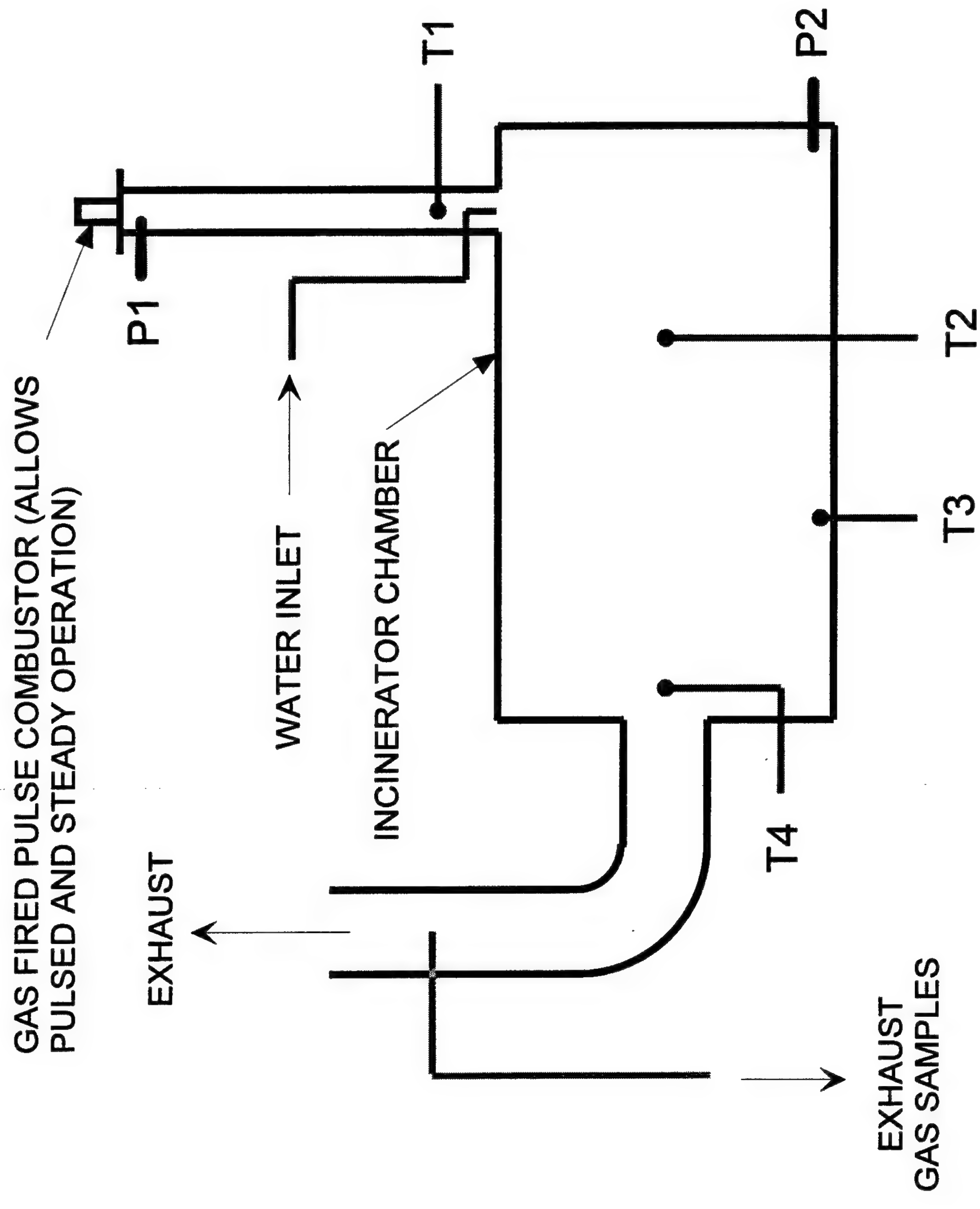


Fig. 28 - Schematic of the experimental setup used for pulsed incineration studies.

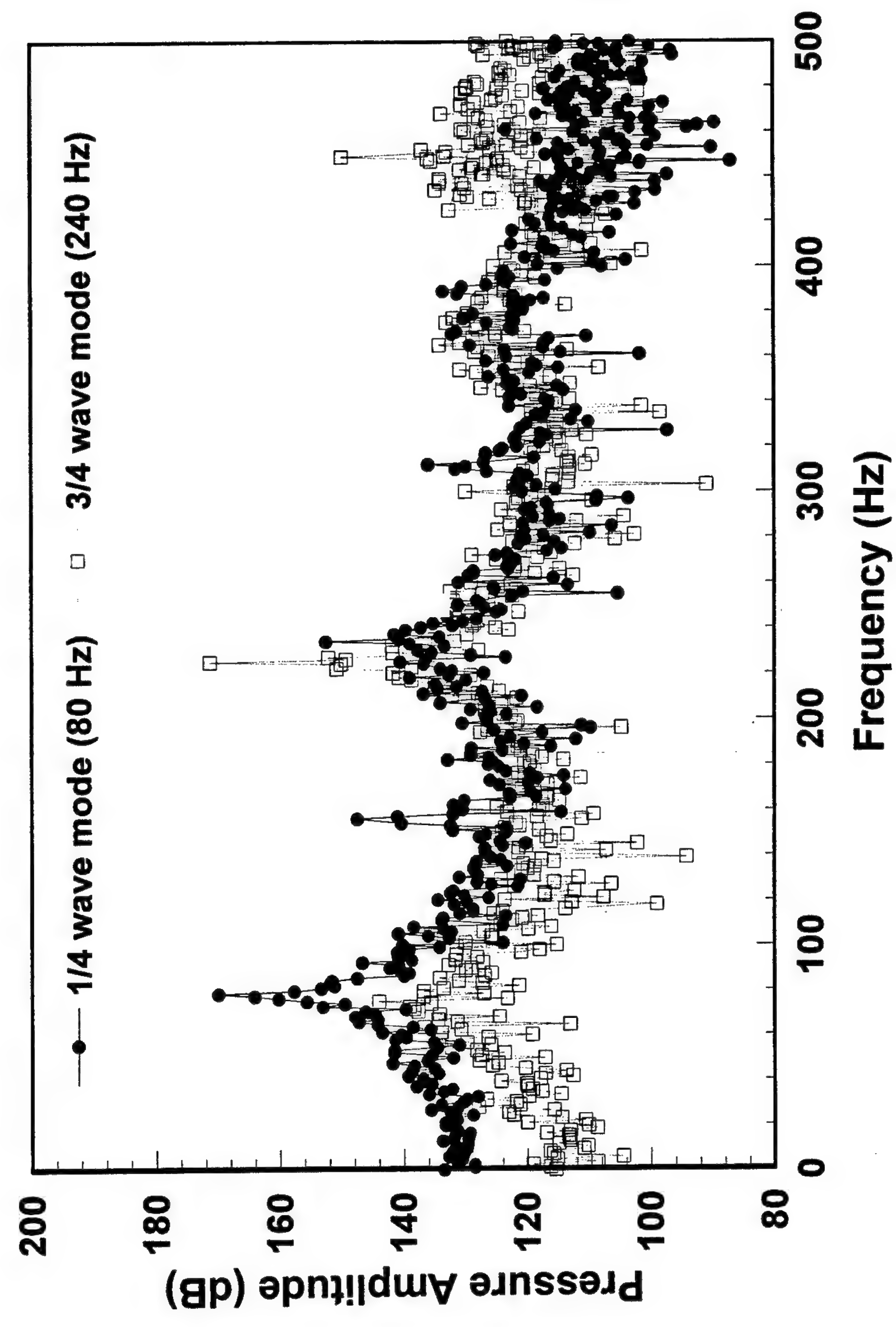


Fig. 29 - Comparison of the acoustic pressure spectra in the gas-fired pulse combustor measured during low and high frequency operation.

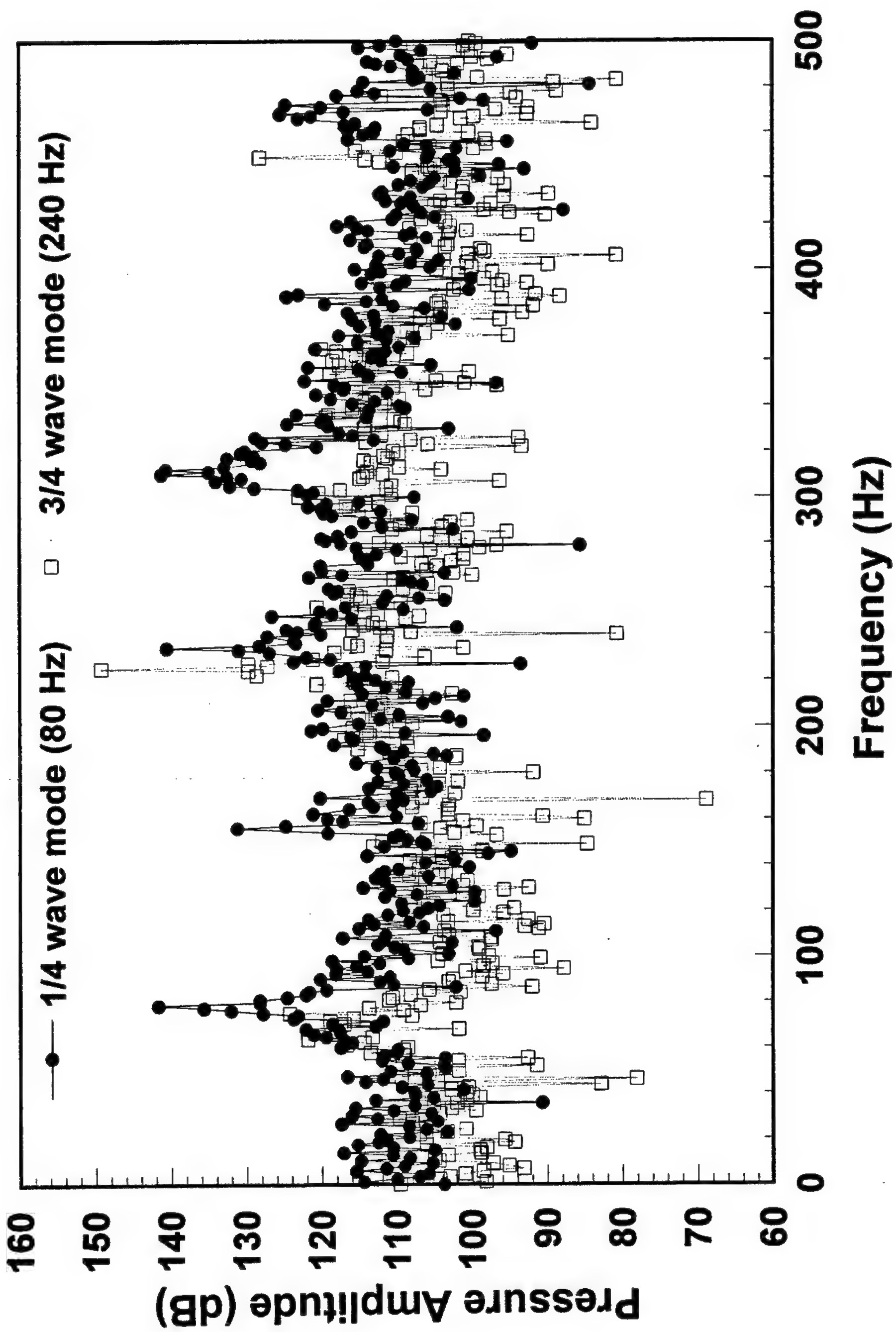


Fig. 30 - Comparison of the acoustic pressure spectra in the incinerator chamber measured during low and high frequency operation.

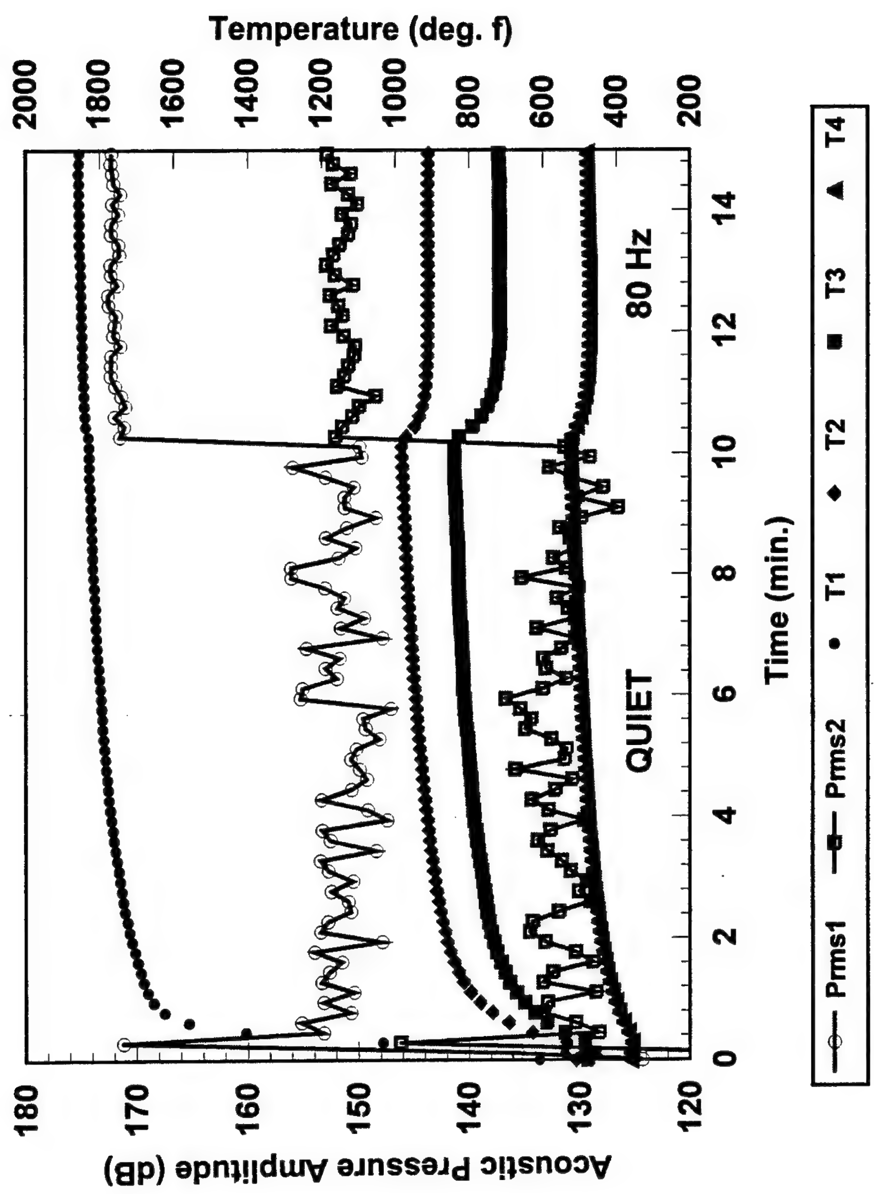


Fig. 31 - Effect of acoustic oscillations on the measured temperatures and acoustic pressures with no spray present.

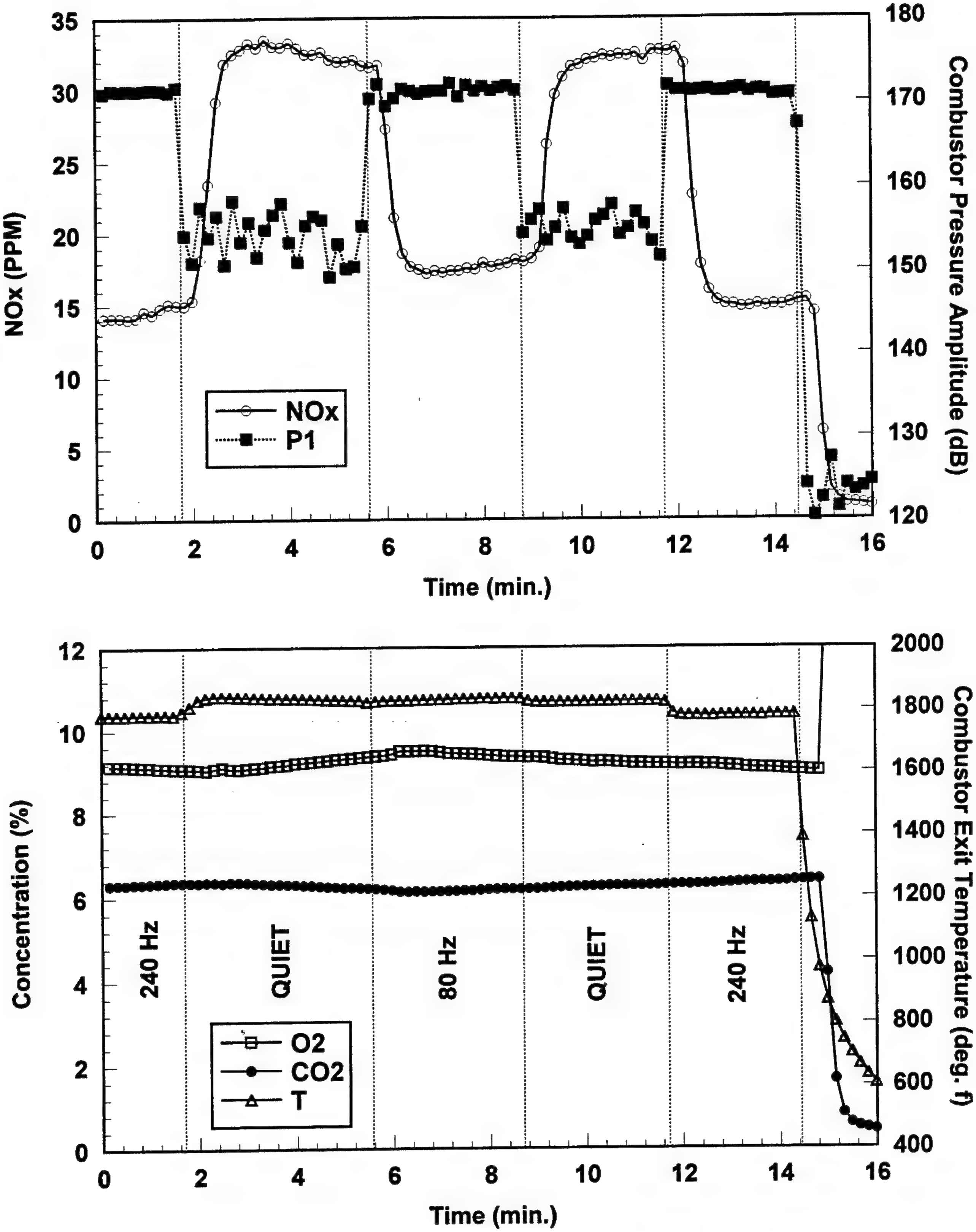


Fig. 32 - Effect on the incinerator emissions of cycling the combustor between pulsed and steady modes of operation.

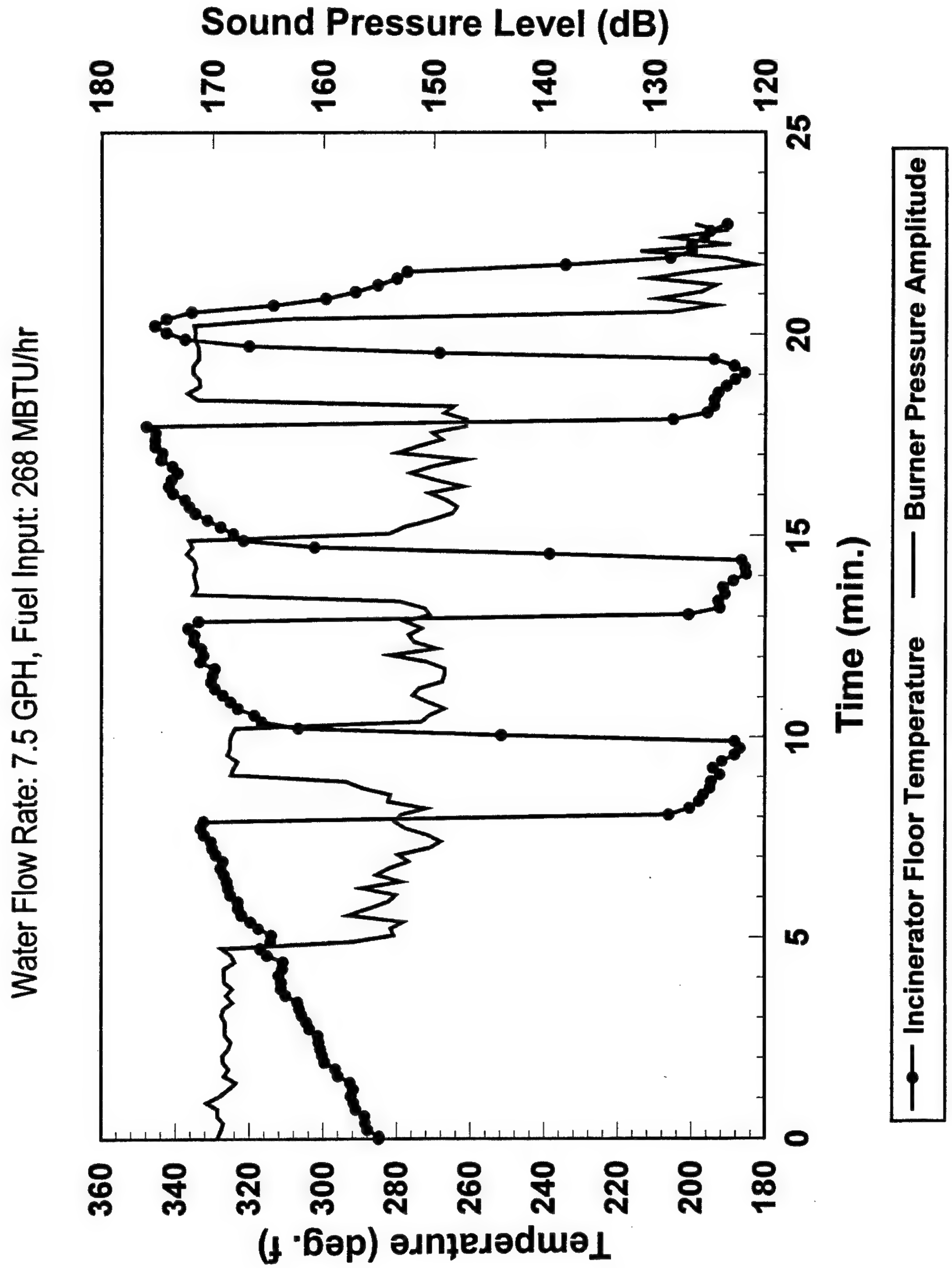


Fig. 33 - Effect on the incineraor floor temperature of cycling the combustor between low frequency pulsed and steady modes of operation due to water pooling.

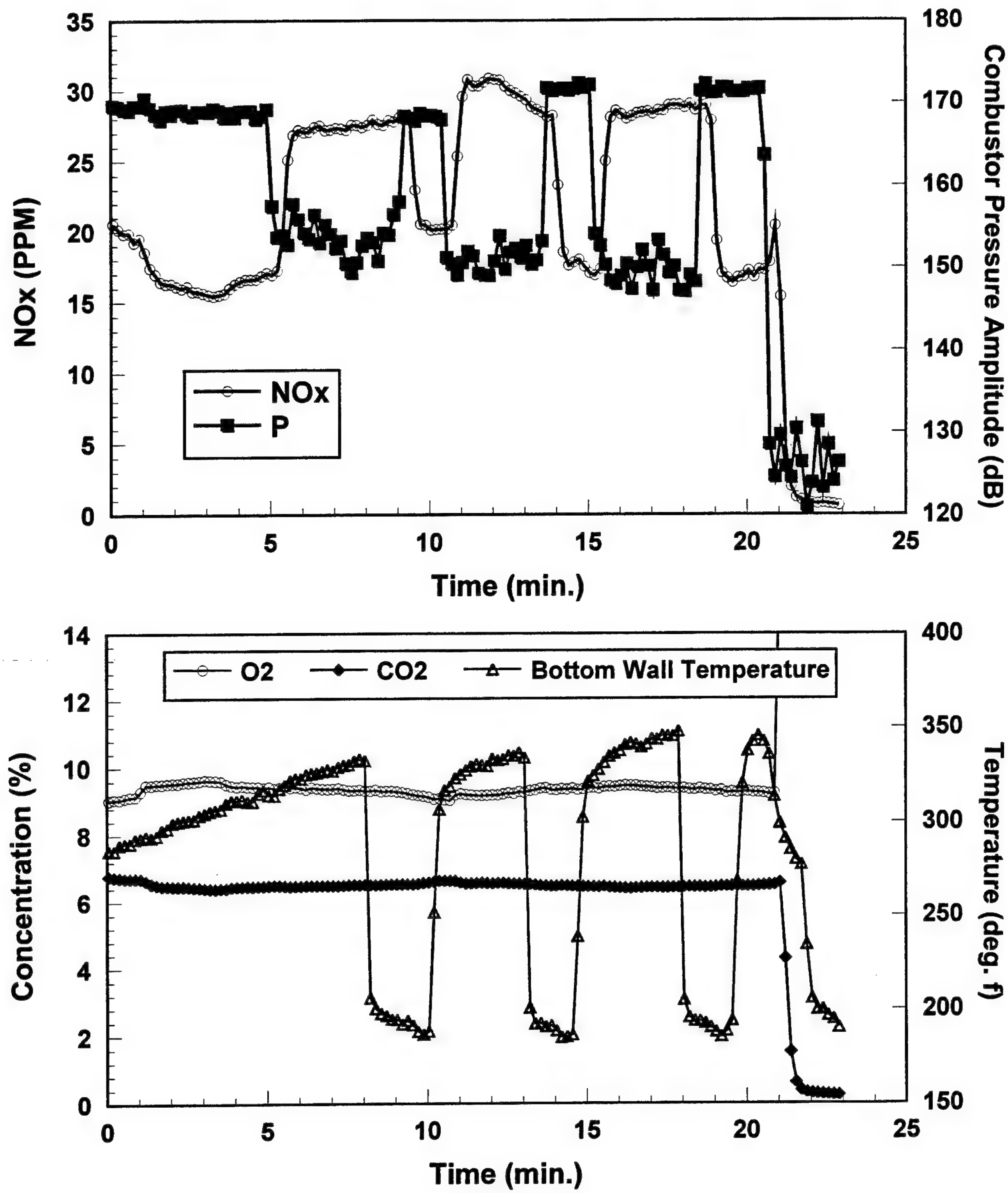


Fig. 34 - Effect on the incinerator emissions of cycling the combustor between pulsed and steady modes of operation.

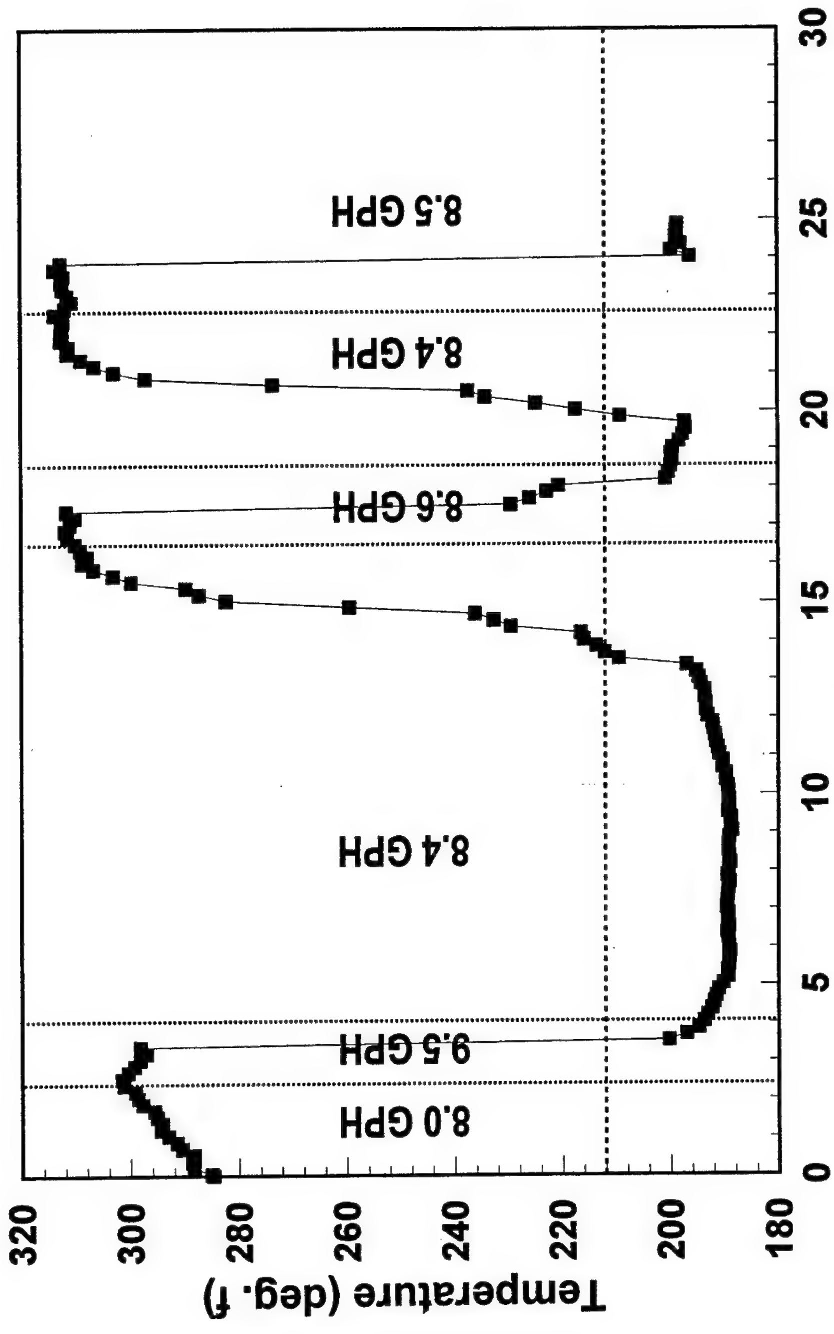
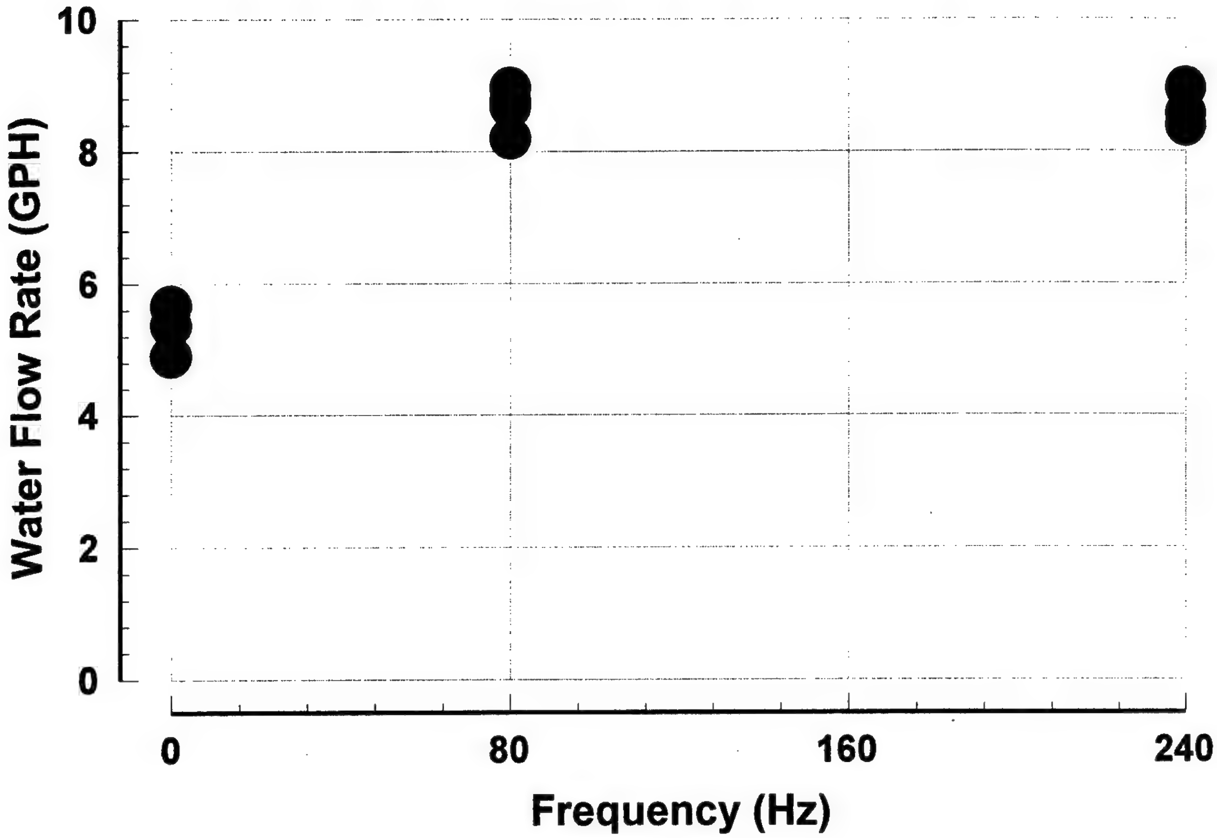


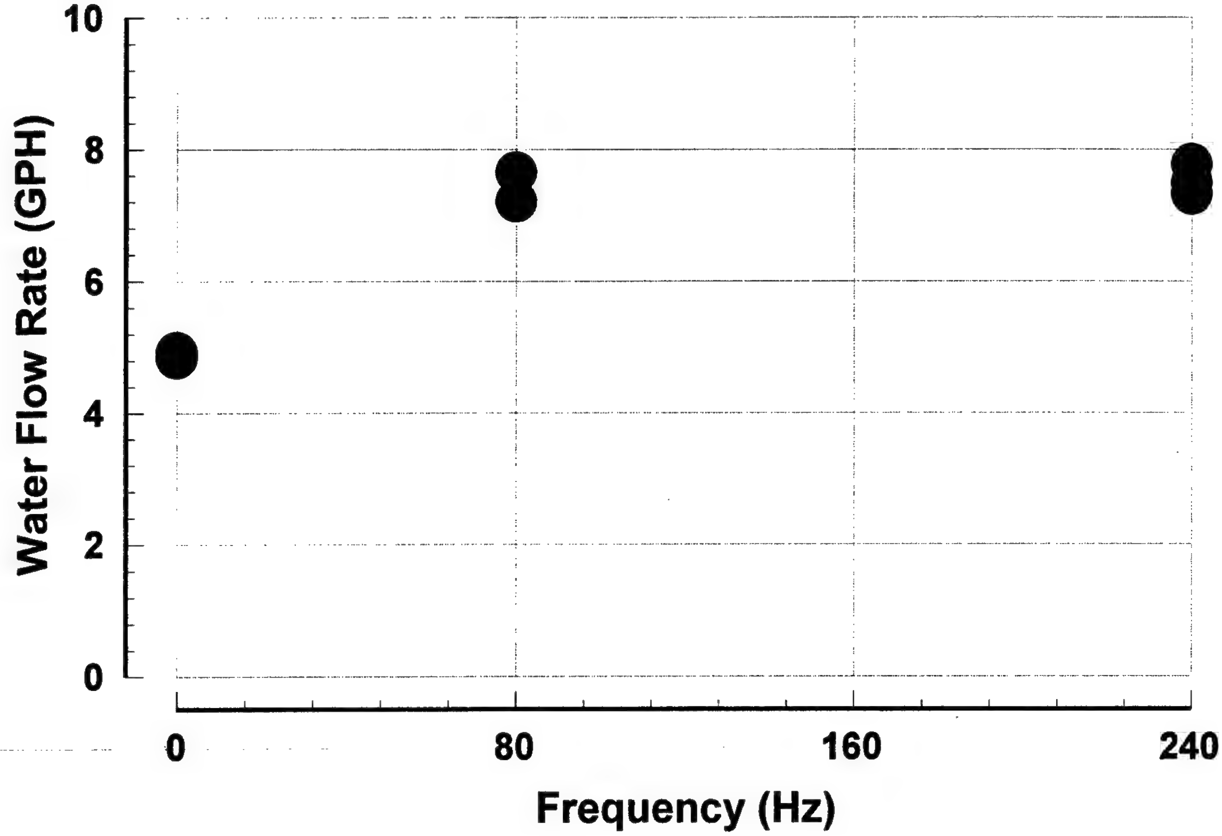
Fig. 35 - Temperature measurements from the bottom surface of the incinerator chamber showing the search process for the maximum evaporation rate.



	steady	1/4 wave	3/4 wave
evaporation rate (GPH)	5.31	8.645	8.637
% efficiency (270 MBTU/hr)	18.48	30.09	30.06
% improvement		62.81	62.65

Note that the improvement in efficiency is proportional to the improvement in throughput.

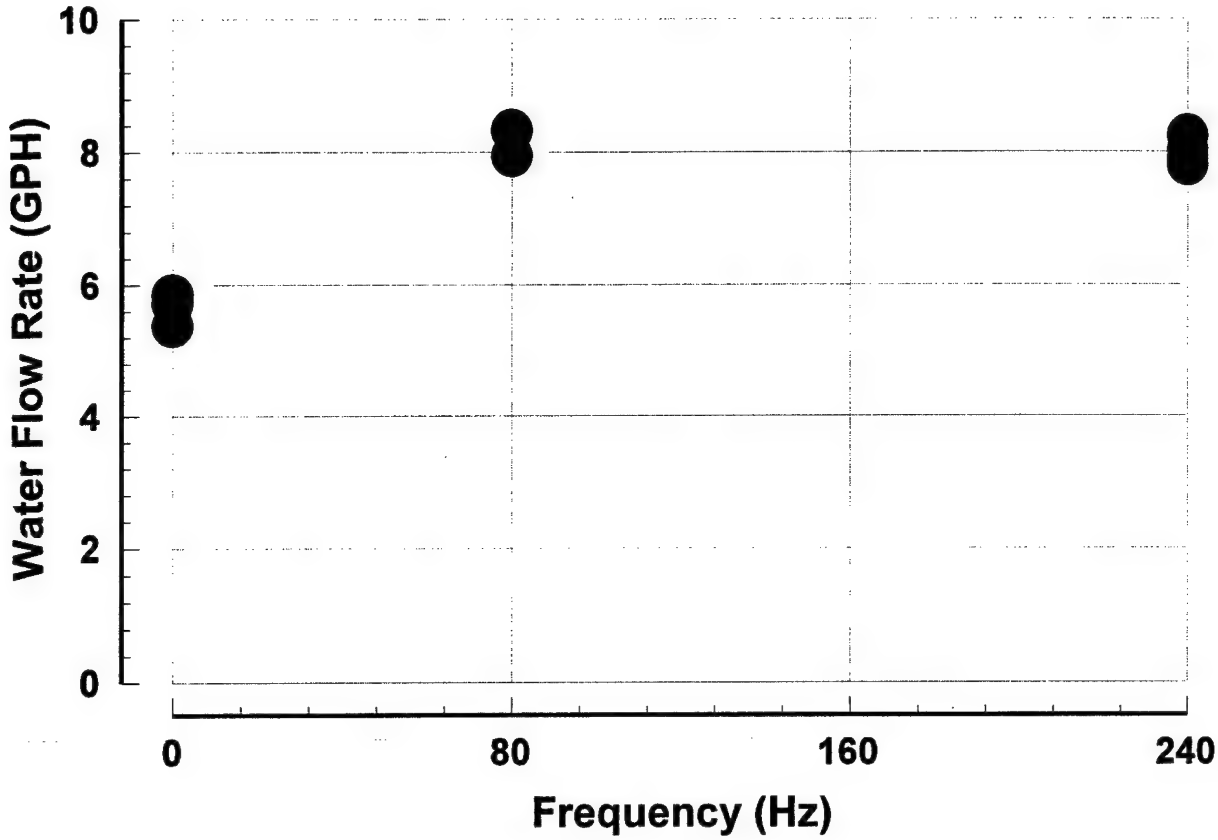
Fig. 36 - Effect of pulsations on the maximum evaporation rate in the model incinerator with a fuel input of 268 MBtu/hr, $\phi = 0.56$



	steady	1/4 wave	3/4 wave
evaporation rate (GPH)	4.89	7.59	7.48
% efficiency (270 MBTU/hr)	21.90	34.00	33.50
% improvement		55	53

Note that the improvement in efficiency is proportional to the improvement in throughput.

Fig. 37 - Effect of pulsations on the maximum evaporation rate in the model incinerator with a fuel input of 208 MBtu/hr, $\phi = 0.56$



	steady	1/4 wave	3/4 wave
evaporation rate (GPH)	5.65	8.21	8.05
% efficiency (270 MBTU/hr)	17.60	25.50	24.90
% improvement		45	42

Note that the improvement in efficiency is proportional to the improvement in throughput.

Fig. 38 - Effect of pulsations on the maximum evaporation rate in the model incinerator with a fuel input of 300MBtu/hr, $\phi = 0.67$

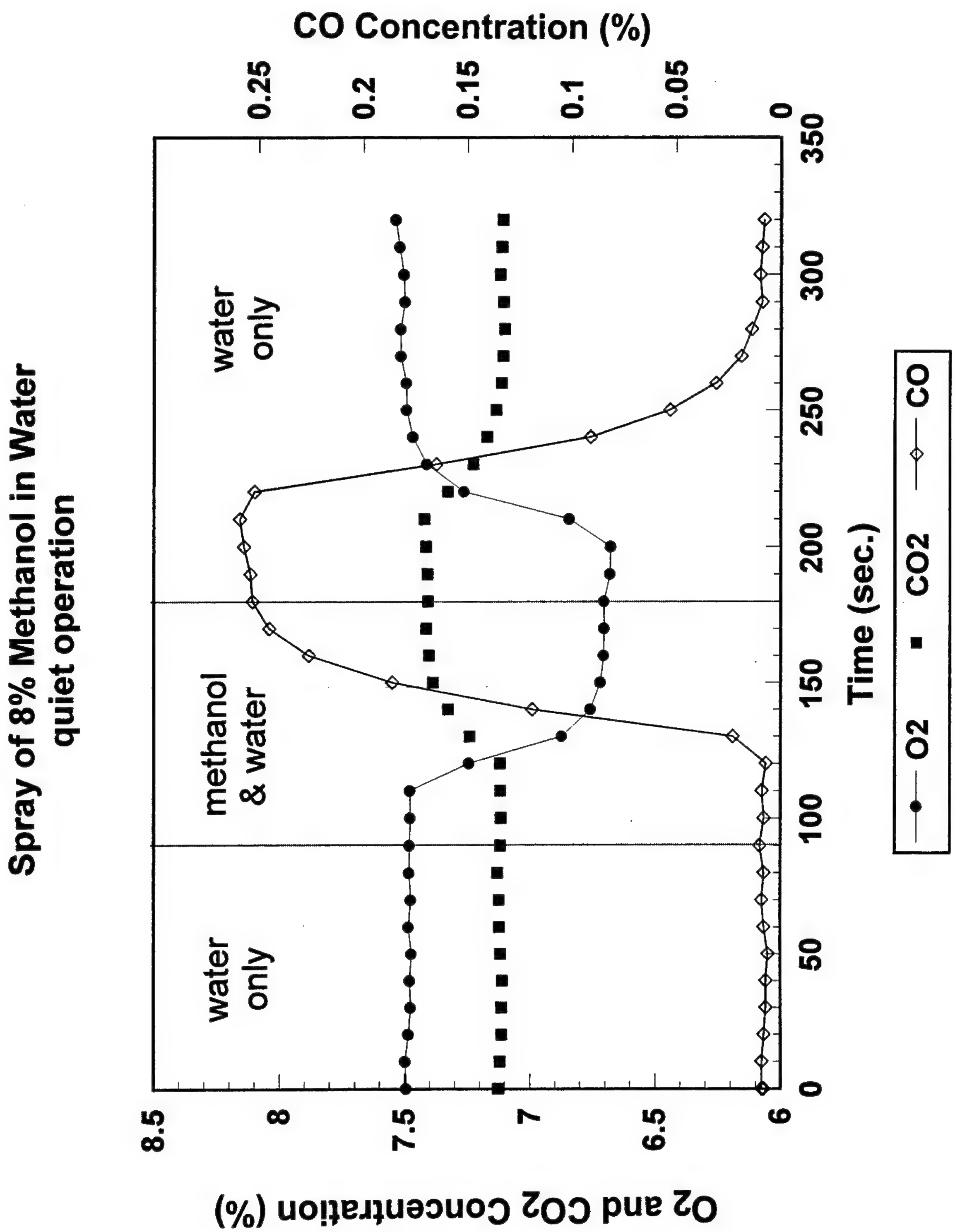


Fig. 39 - Exhaust gas concentrations while burning methanol in steady operating mode.

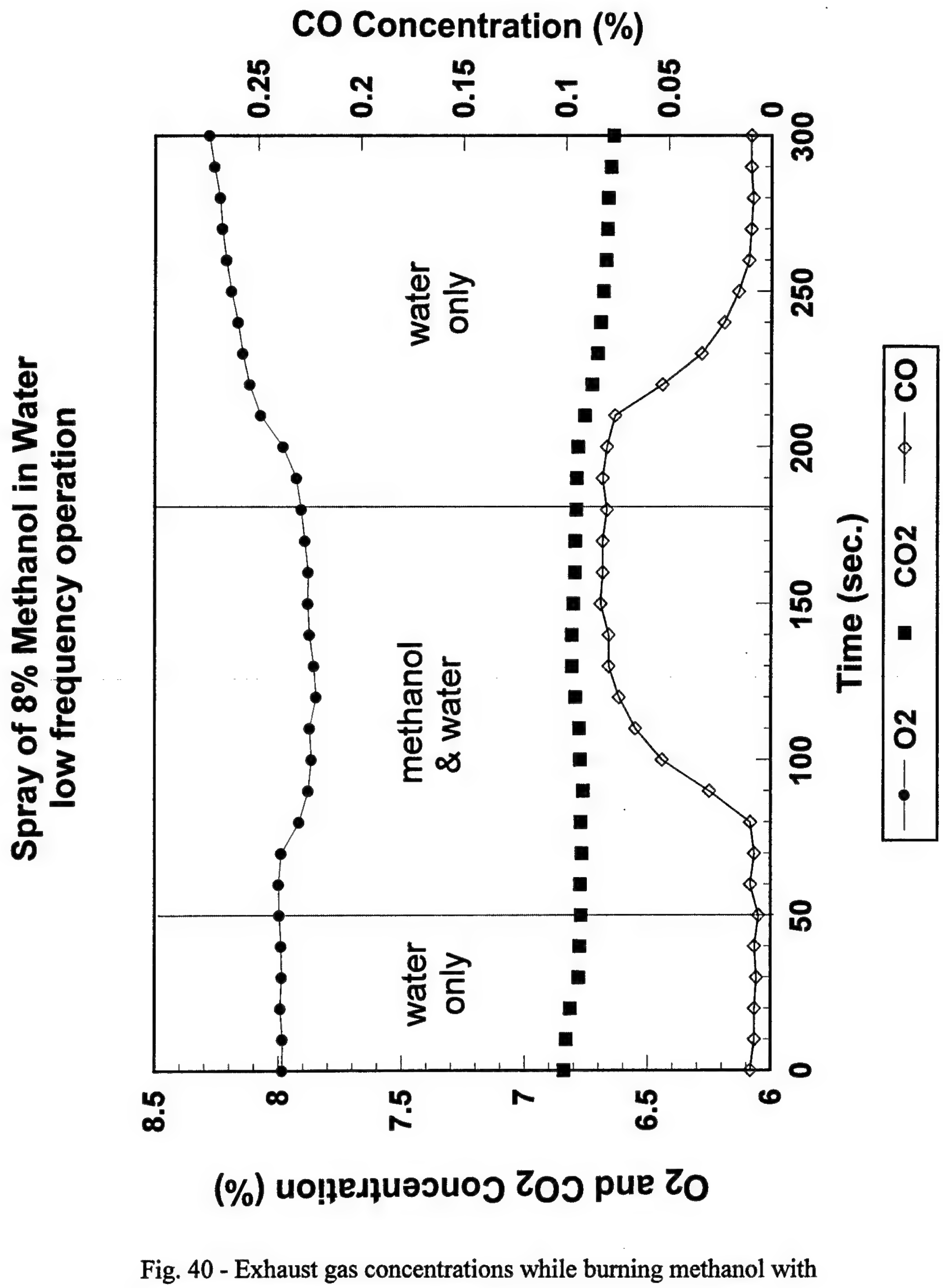


Fig. 40 - Exhaust gas concentrations while burning methanol with low frequency acoustic forcing.

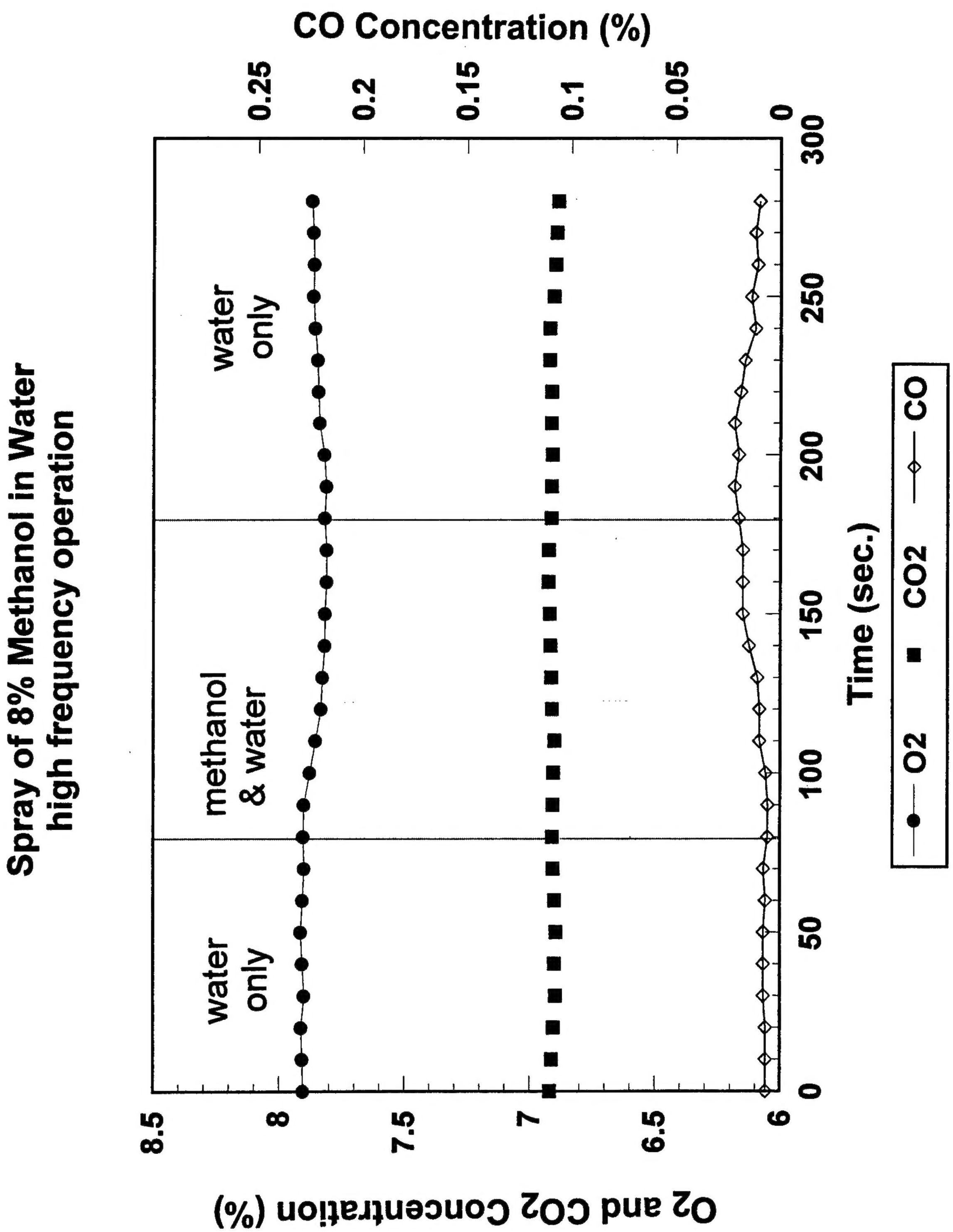


Fig. 41 - Exhaust gas concentrations while burning methanol with high frequency acoustic forcing.

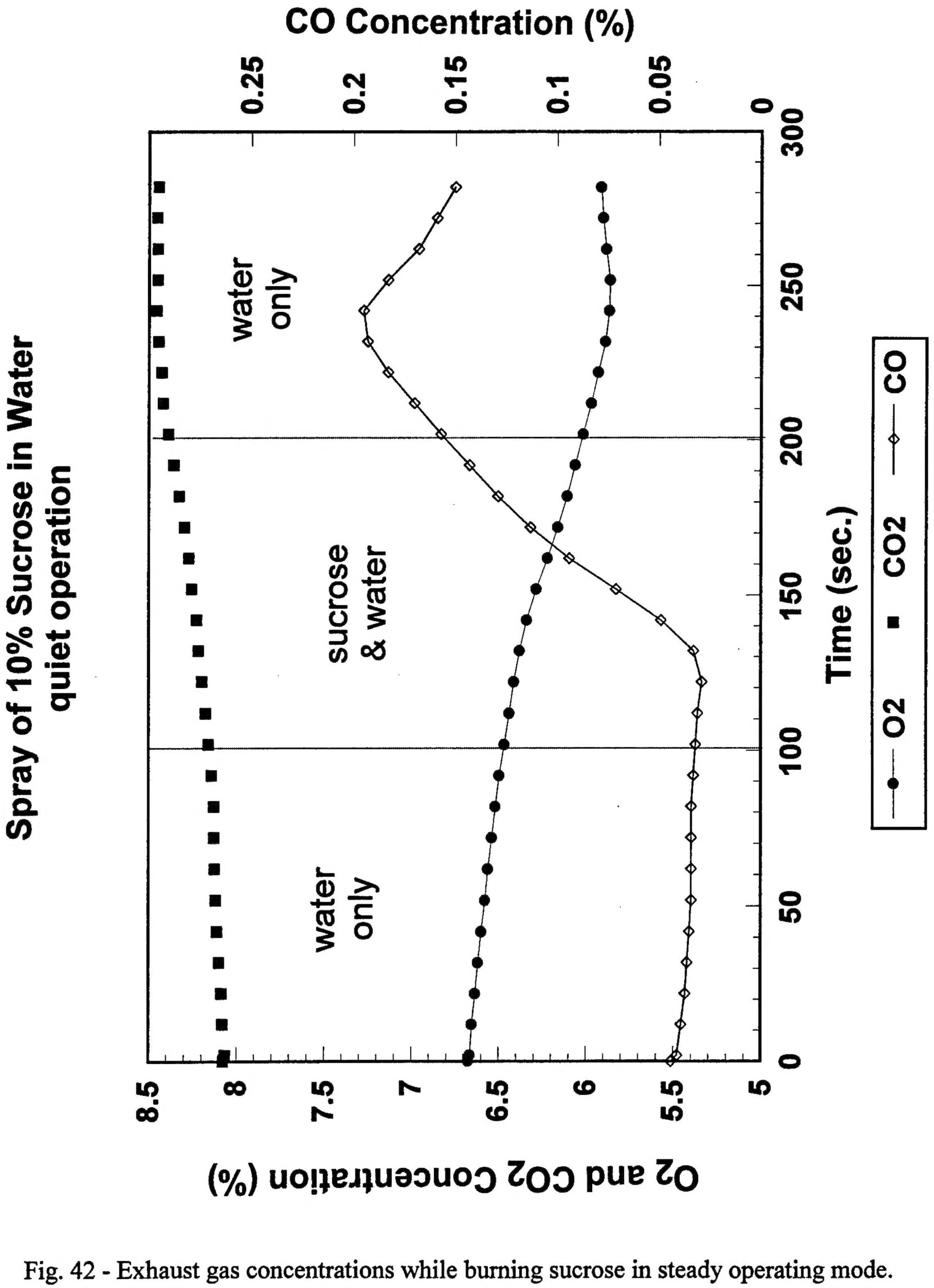


Fig. 42 - Exhaust gas concentrations while burning sucrose in steady operating mode.

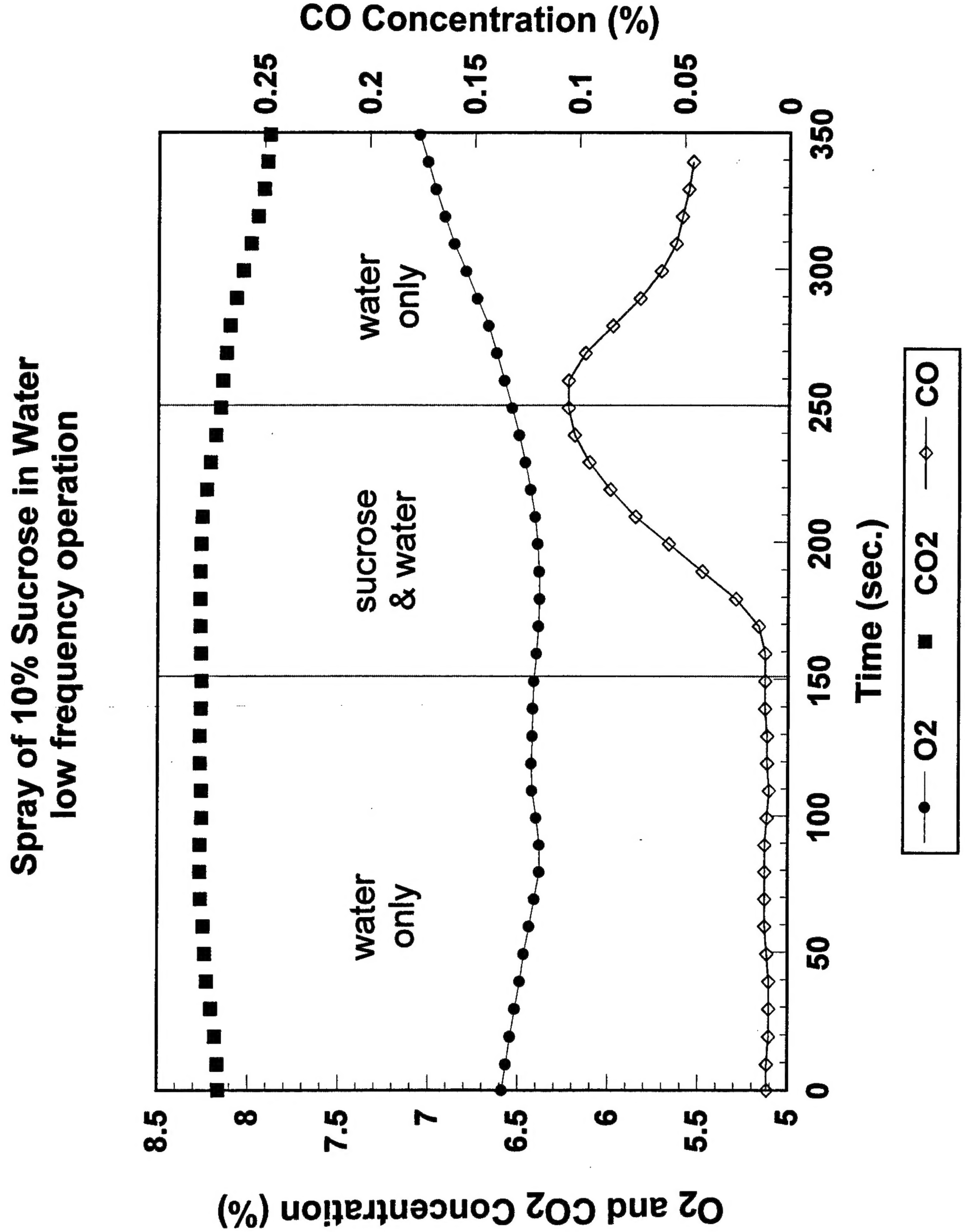


Fig. 43 - Exhaust gas concentrations while burning sucrose with low frequency acoustic forcing.

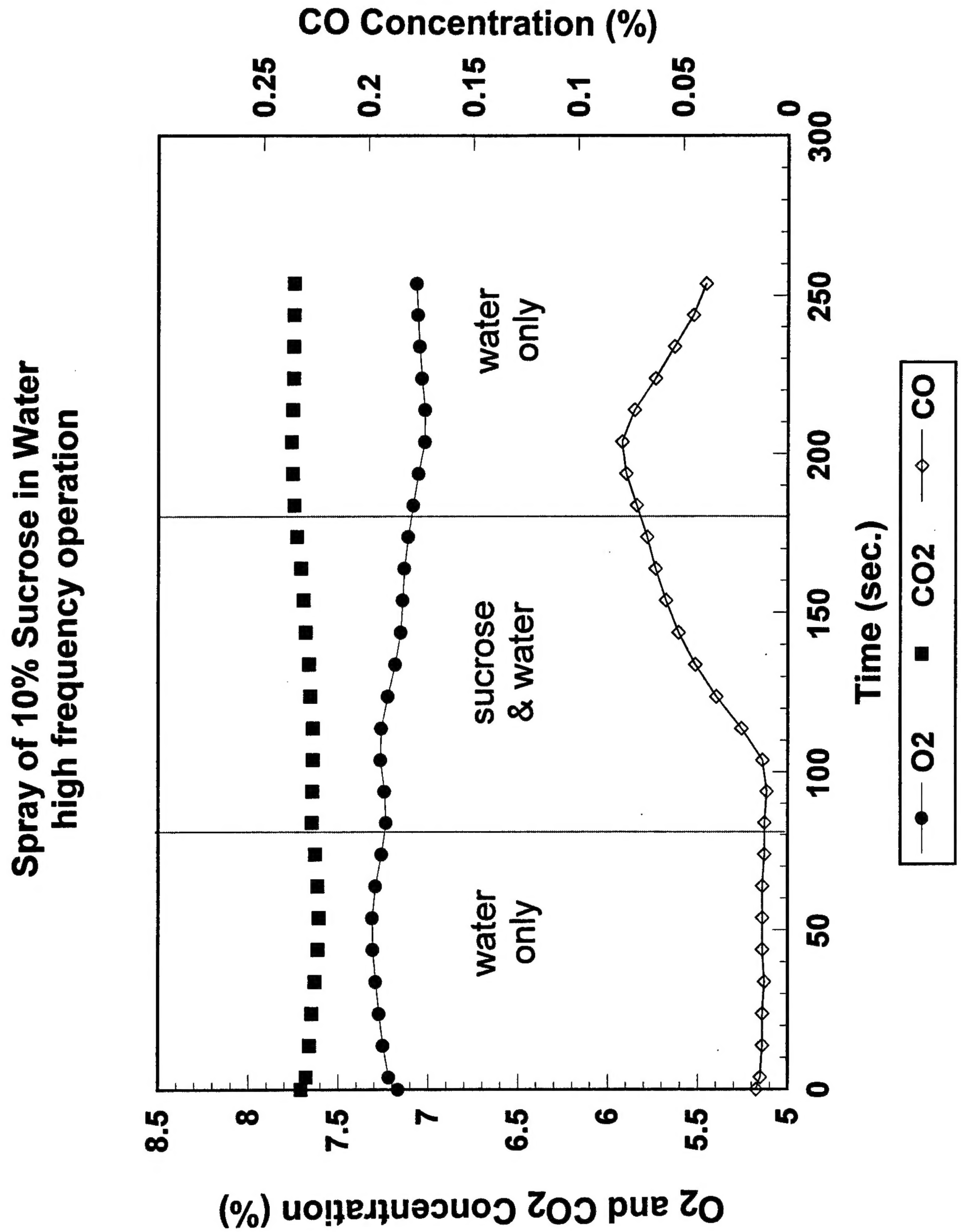


Fig. 44 - Exhaust gas concentrations while burning sucrose with high frequency acoustic forcing.